Telescopes and Optical Systems

Goals of a telescope:

- To collect as much light as possible
- To bring the light to as sharp a focus as possible

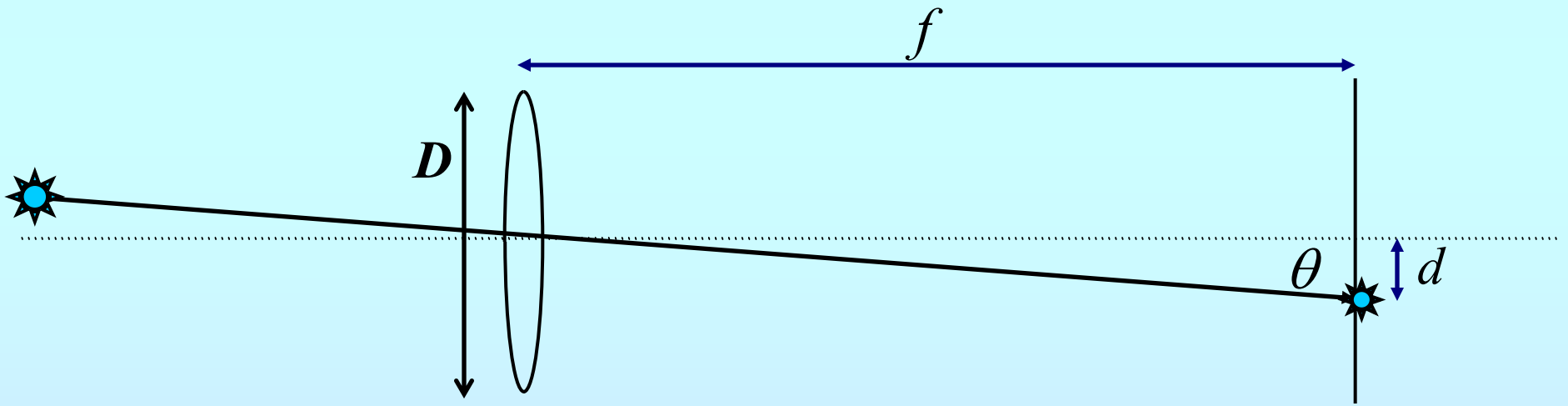
Numbers to keep in mind:

- ~ 206,265 arcsec in a radian
- 1.22 = coefficient for Airy ring

Telescopes and Optical Systems

Key Parameters in defining a telescope:

- Aperture diameter, ***D*** (light collected goes as $\boldsymbol{D}^2$)
- Focal length, ***f***
- The f-ratio (= ***f*** / ***D***). "Fast" telescopes have small f-ratios.
- Plate scale, ***p*** (generally given in arcsec/pixel or arcsec/mm)



$$d = f\tan\theta \approx f\theta \quad \Rightarrow \quad p = \frac{1}{f\theta''} = \frac{206265''}{f} = \frac{206265''}{D \times \text{f-ratio}}$$

Resolved Objects

The observed size of a resolved object (such as a galaxy, a nebula, a planet, etc.) is given by the plate scale. For a source with angular size θ, the area subtended by the object on the detector is

$$s \propto \frac{\theta}{p} \propto D \times \text{f-ratio} \Rightarrow s^2 \propto \left(D \times \text{f-ratio}\right)^2$$

The amount of light collected by the telescope is simply

$$E \propto D^2$$

So the light per unit area on the detector is then

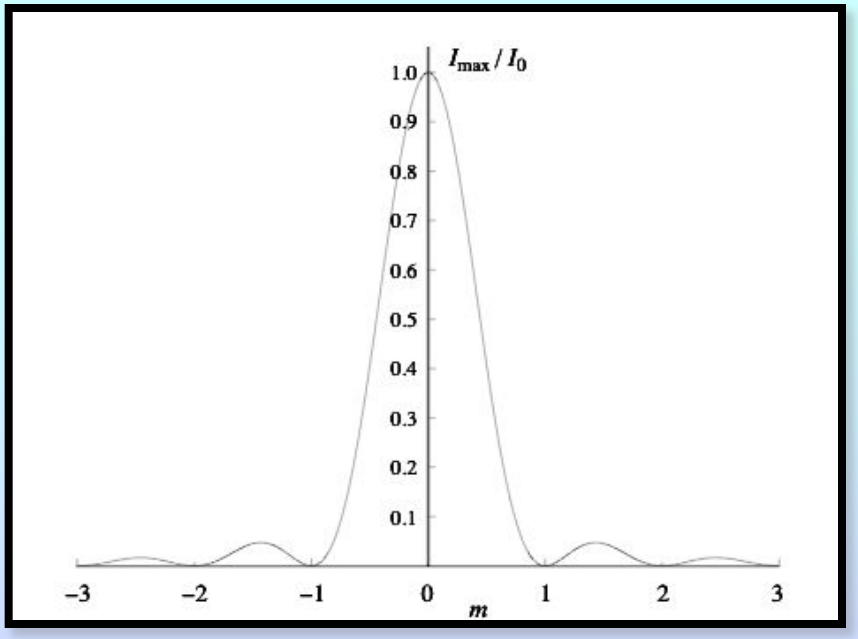
$$\frac{E}{s^2} \propto \frac{D^2}{\left(D \times \text{f-ratio}\right)^2} \propto \frac{1}{\left(\text{f-ratio}\right)^2}$$

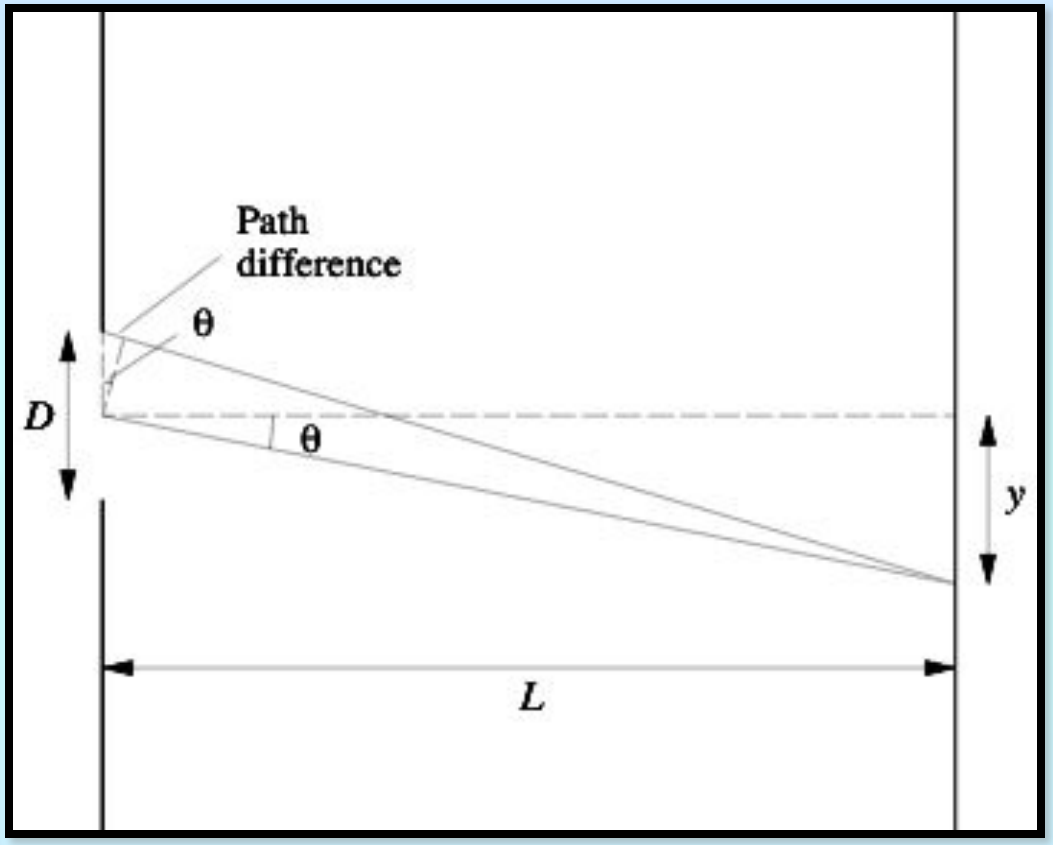
Note that the brightness per unit area is independent of aperture size, but sensitive to the f-ratio. The faster the telescope, the brighter the object. (Using a bigger telescope does not always help).

Diffraction

There is a limit to the resolution attainable by a telescope.

Light of wavelength λ entering an aperture of diameter ***D***, will undergo destructive interference due to the different path lengths.

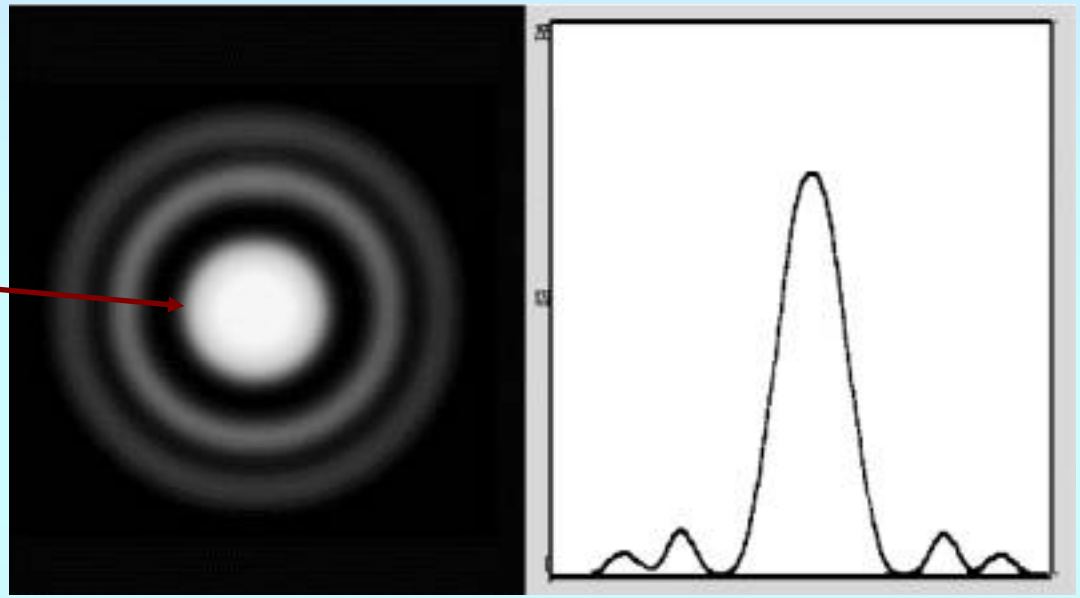




$$\frac{D}{2}\sin\theta = \frac{\lambda}{2} \Rightarrow \sin\theta \approx \theta = m\frac{\lambda}{D}$$

Airy Rings

For diffraction through a *circular* aperture, the result is the **Airy diffraction pattern**:



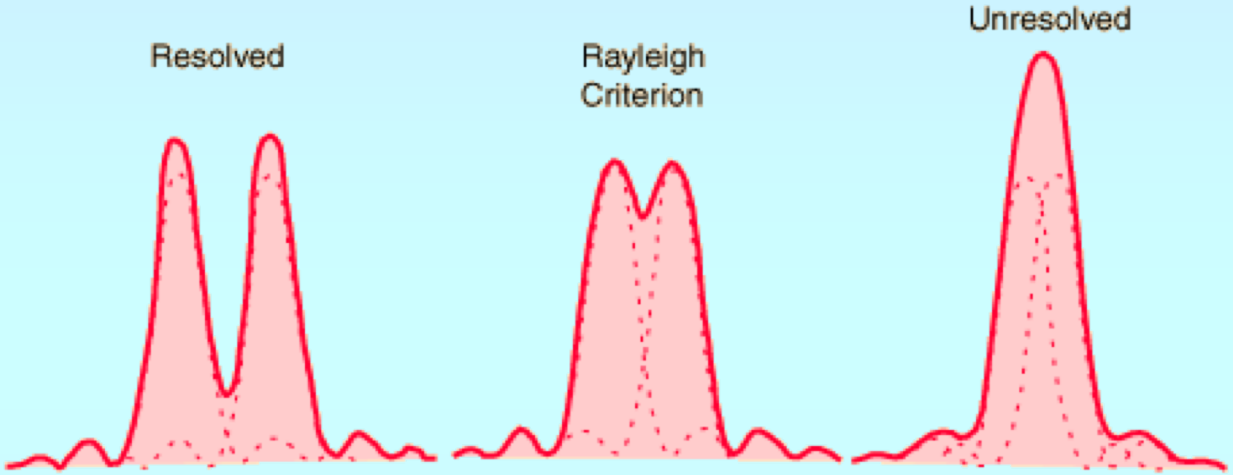
About 84% of the total light falls within the central Airy disk. (For comparison, the second peak is ~2% the intensity of the first!) The radius of this disk is

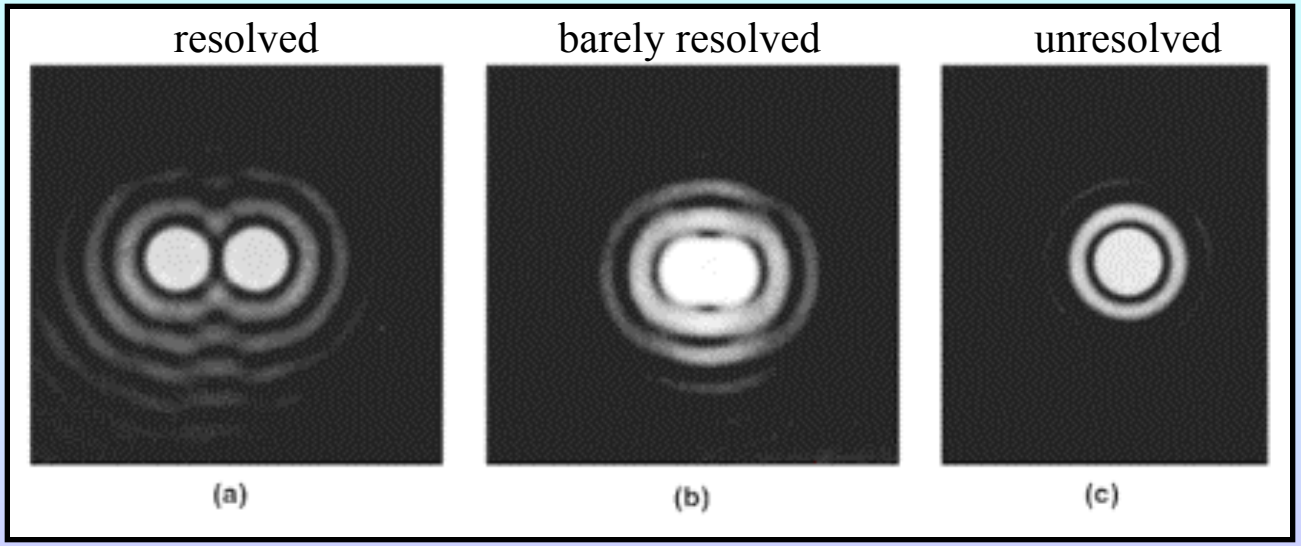
$$\theta = 1.22\frac{\lambda}{D}$$

This is a fundamental limit to the size of point sources.

Rayleigh Criterion for Resolution

If two point sources are close together, the result is a superposition of Airy patterns. The ***Rayleigh criterion*** is when the peak of one pattern is at the first minimum of the second.

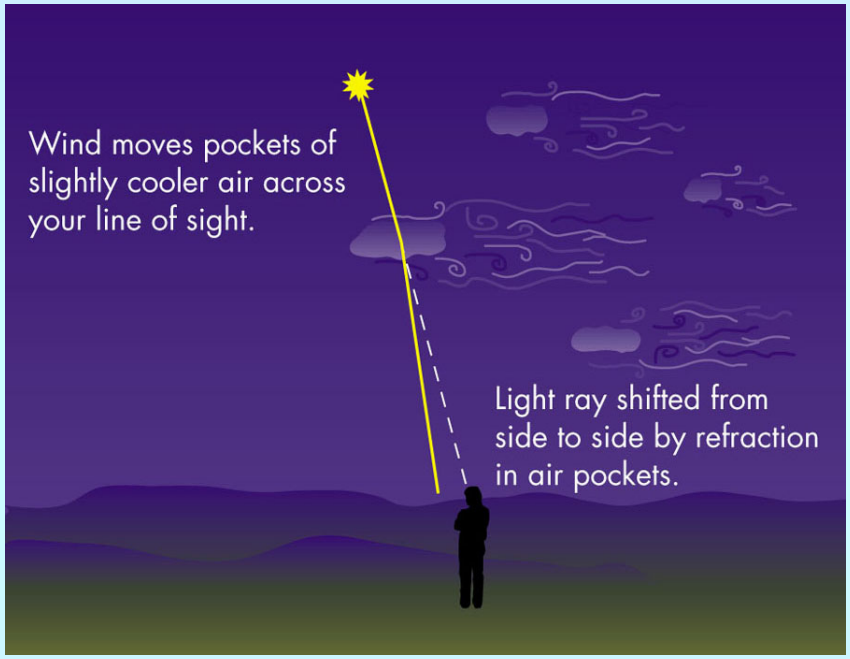


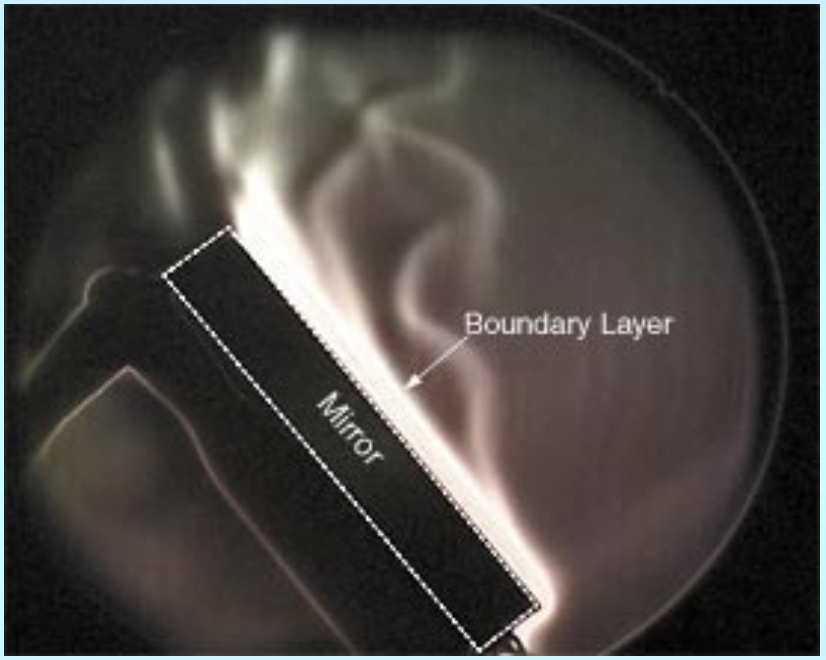


$$\theta = 1.22\frac{\lambda}{D}$$

Seeing

At optical (and near-IR) wavelengths, atmospheric turbulence limits the attainable resolution (due to rapid image motion and blurring).

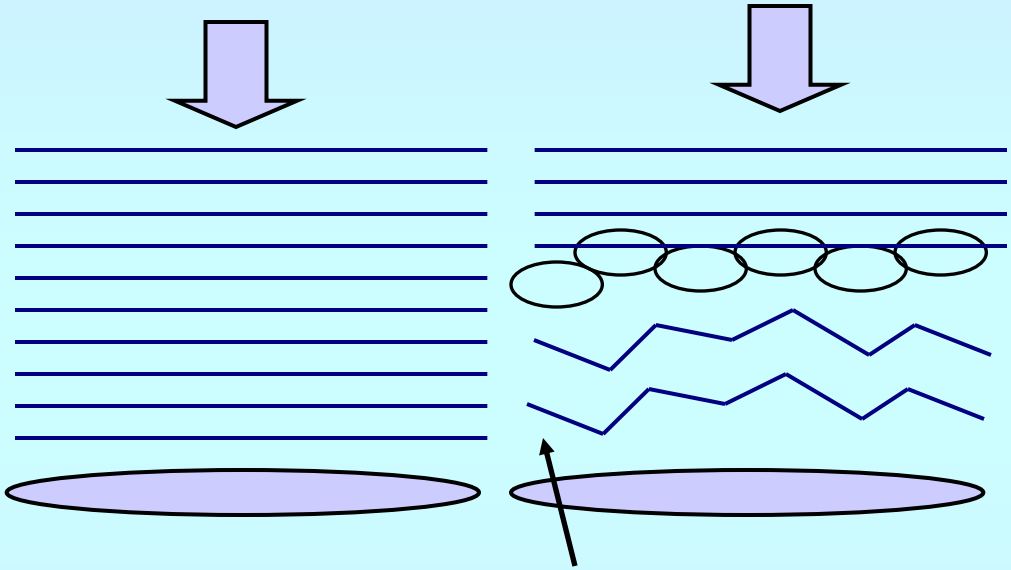




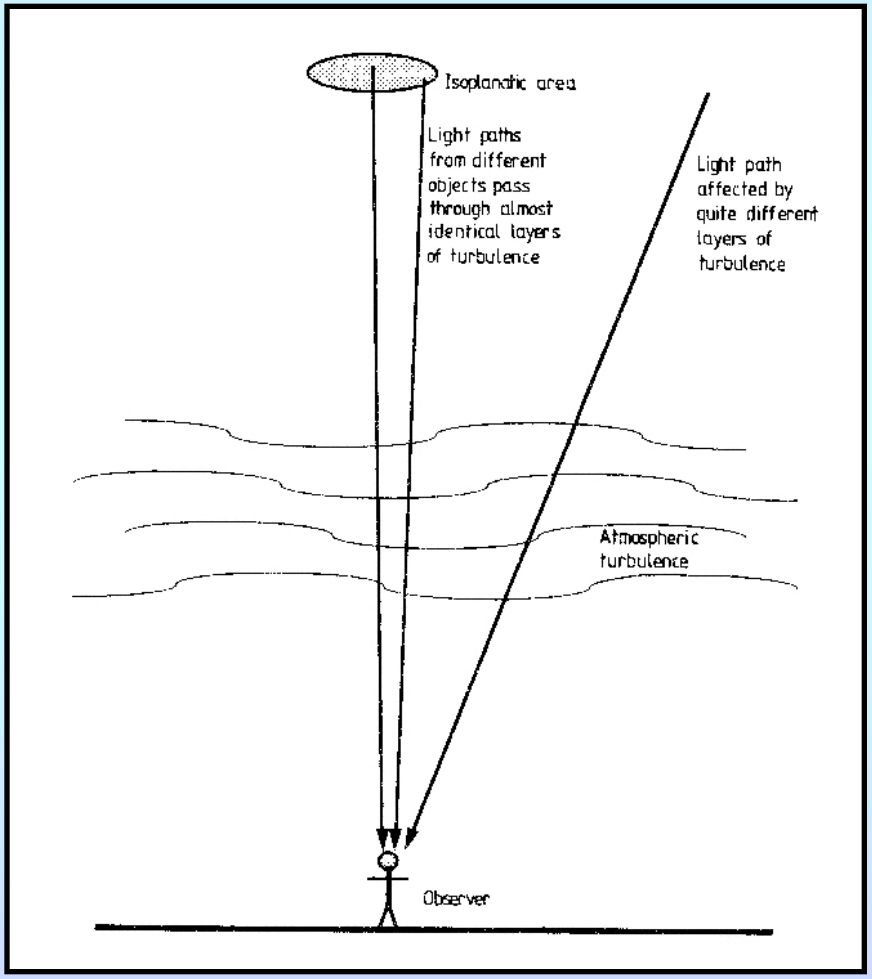
Seeing is caused both by the full atmosphere and by the convective motions of air within/near the telescope, i.e., "dome seeing". (The latter effect was not fully realized until the 1970's.) The *best* ground-based seeing is ~ 0.5″. In general, the bluer the wavelength, the worse the seeing.

The Physics of Seeing

The atmosphere has moving density variations, which vary the light's optical path. This distorts the wavefront on scales larger than ~10-20 cm in the optical (~1 meter in the IR).

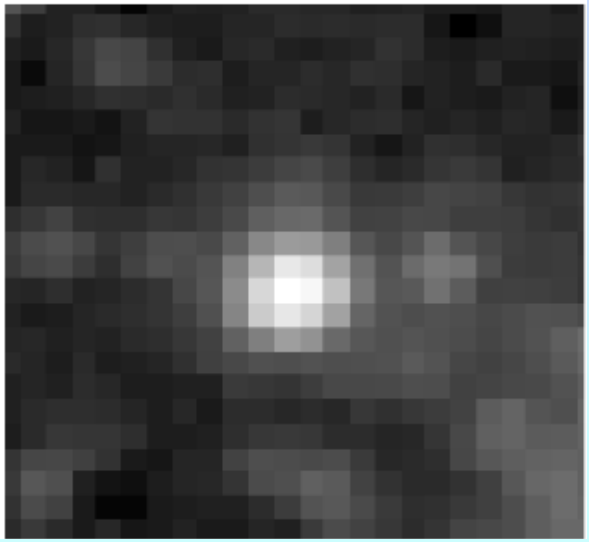


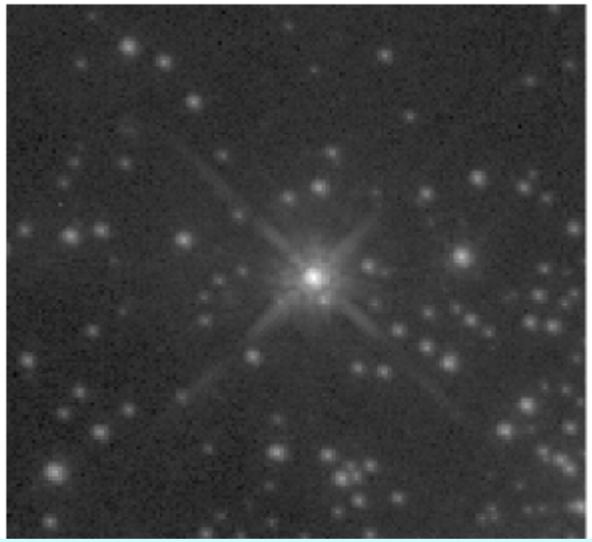
d_0 ~ 10 cm distorted wavefront

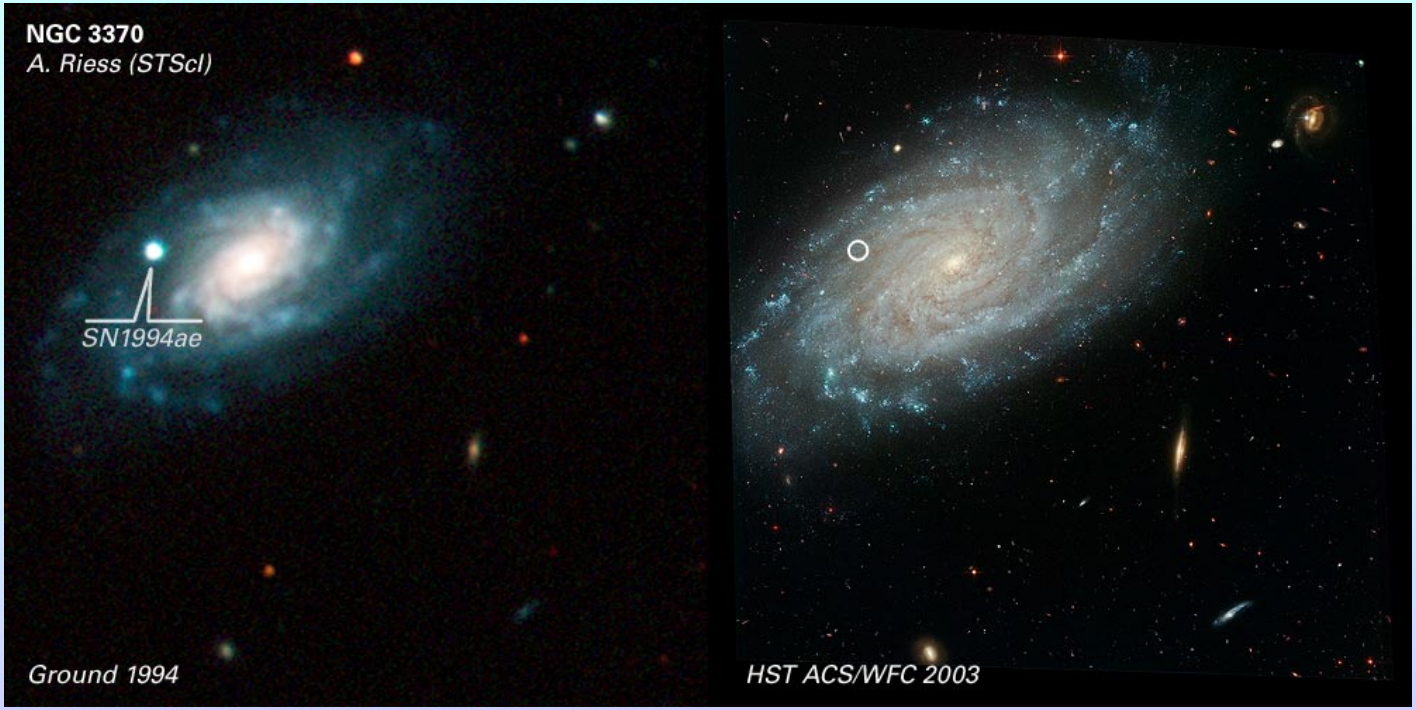


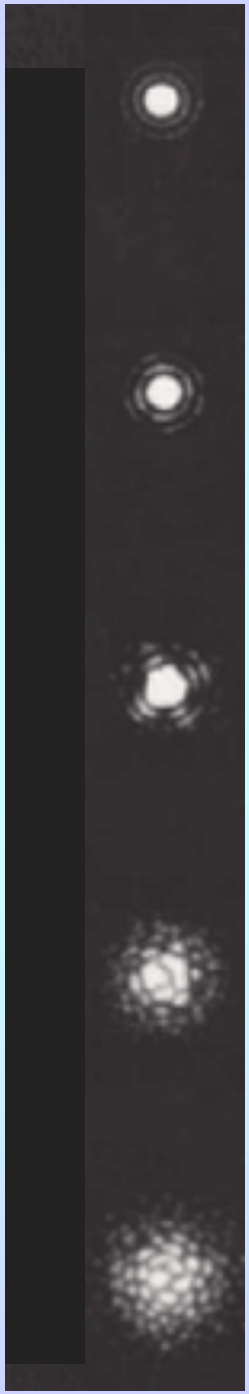
The bluer the wavelength, the smaller the "isoplanic patch," and the more difficult it is to correct for seeing.

Effects of Seeing





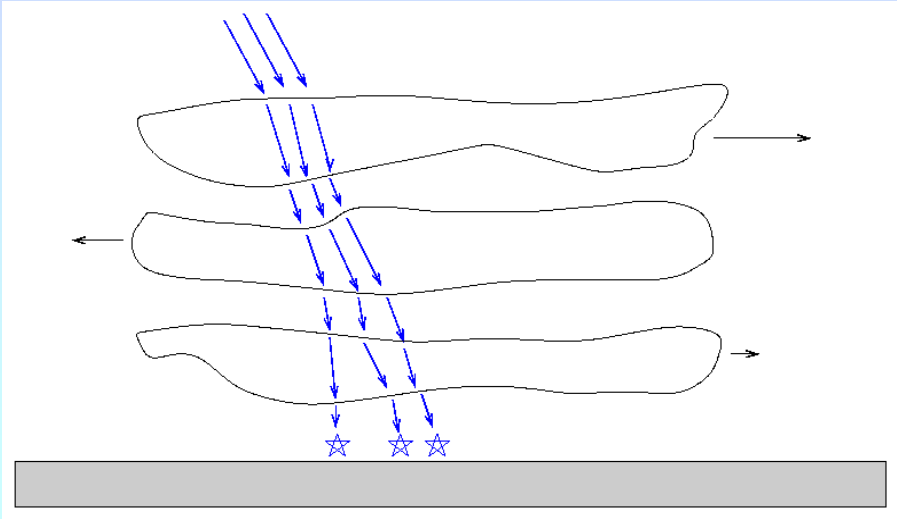


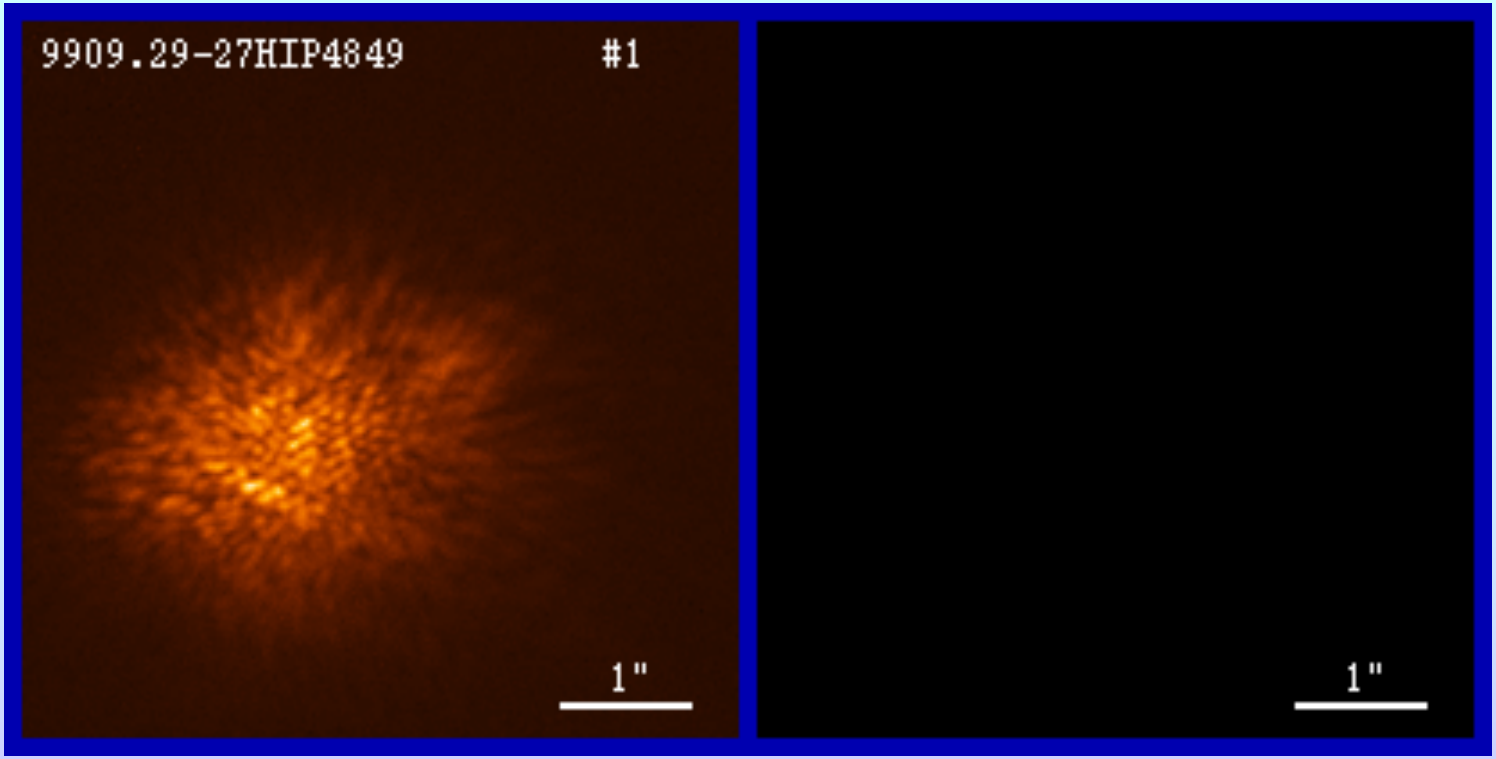


Correcting for Seeing

To compensate (at least partially) for seeing, one can

- Take very short (~20 millisec) exposures, then align and add up the individual frames ("speckle")





Correcting for Seeing

To compensate (at least partially) for seeing, one can

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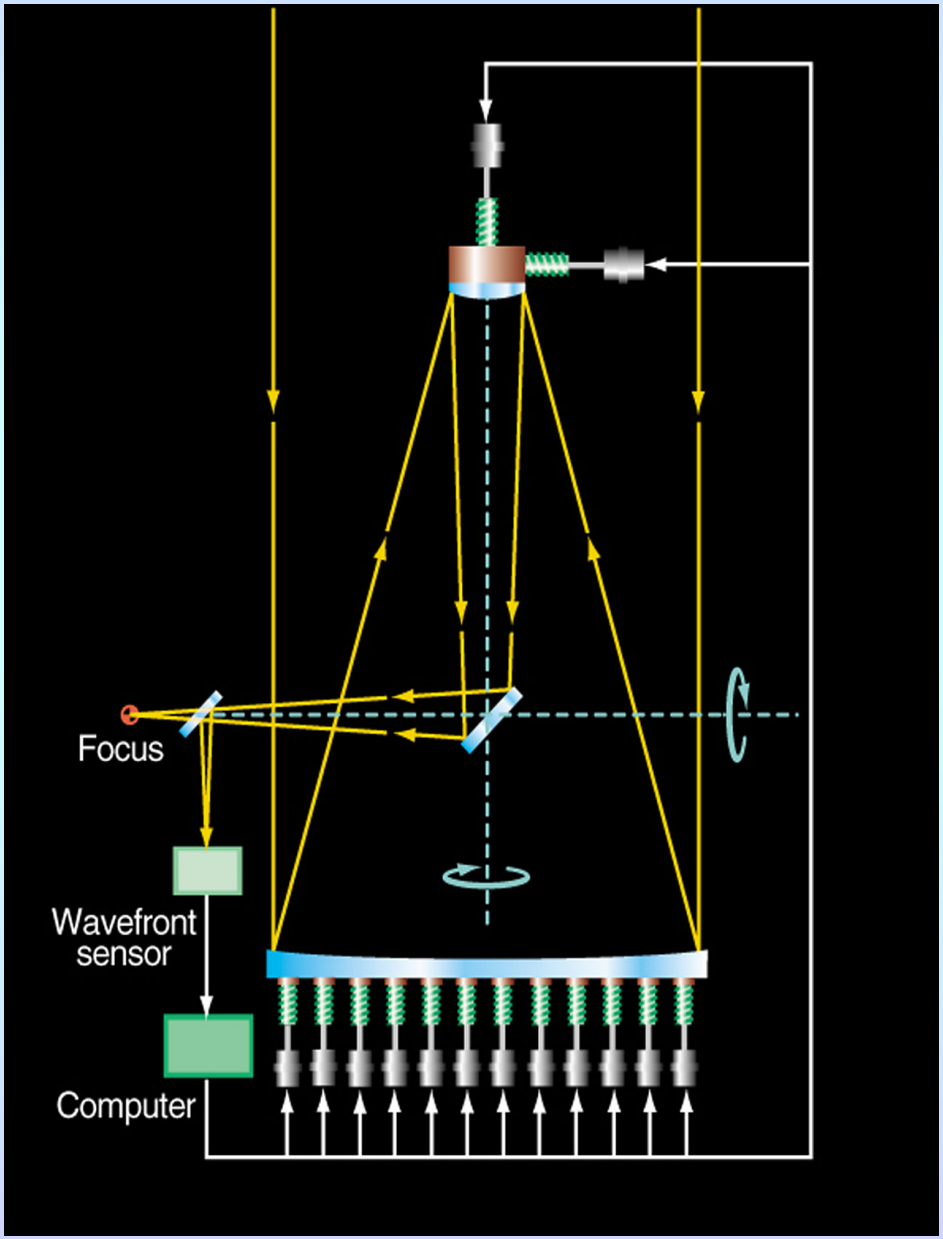
- Sense the wavefront and use actuators to realign the mirrors every ~ 0.5 sec ("active optics")



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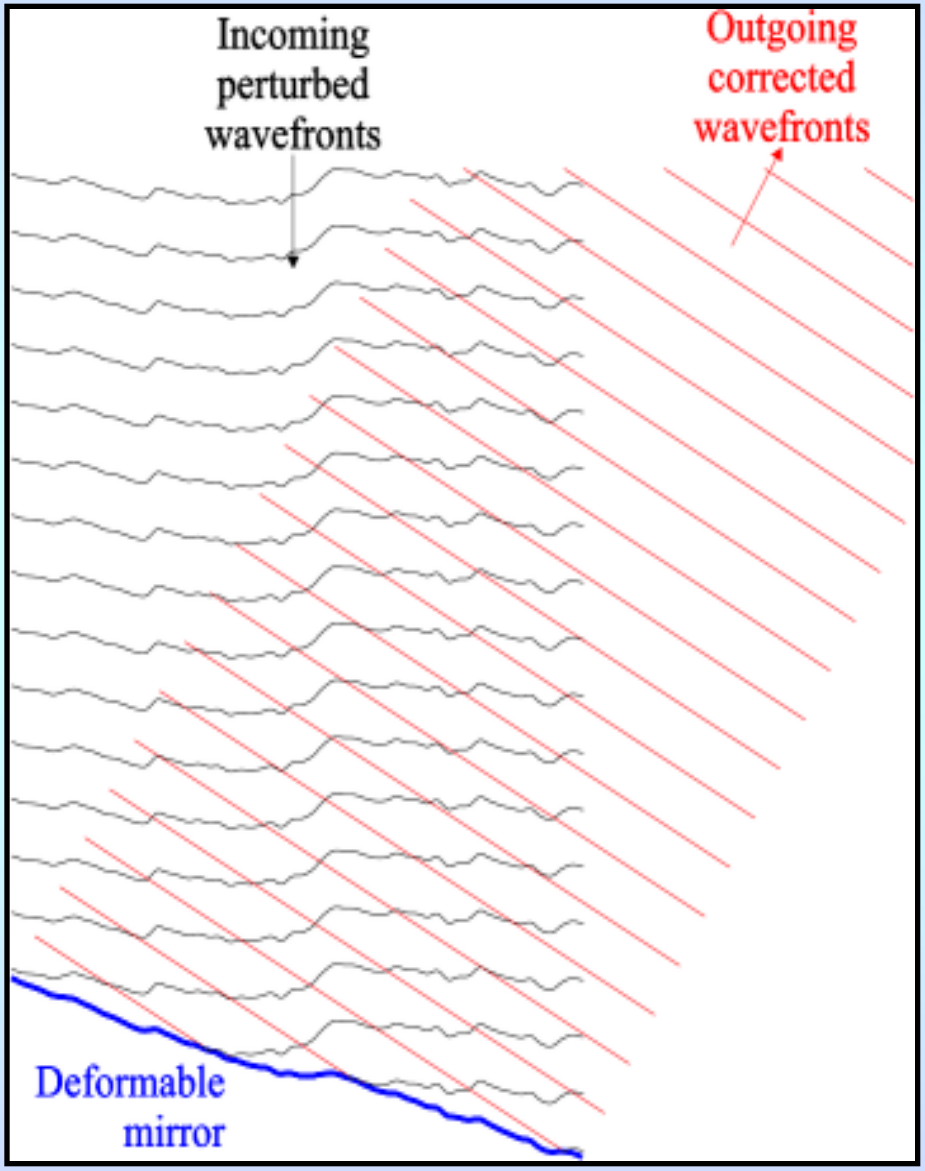
- Sense, then correct the wavefront by deforming one of the mirrors every millisec ("adaptive optics"). Because of the size of the isoplanic patch, this is much easier in the IR.



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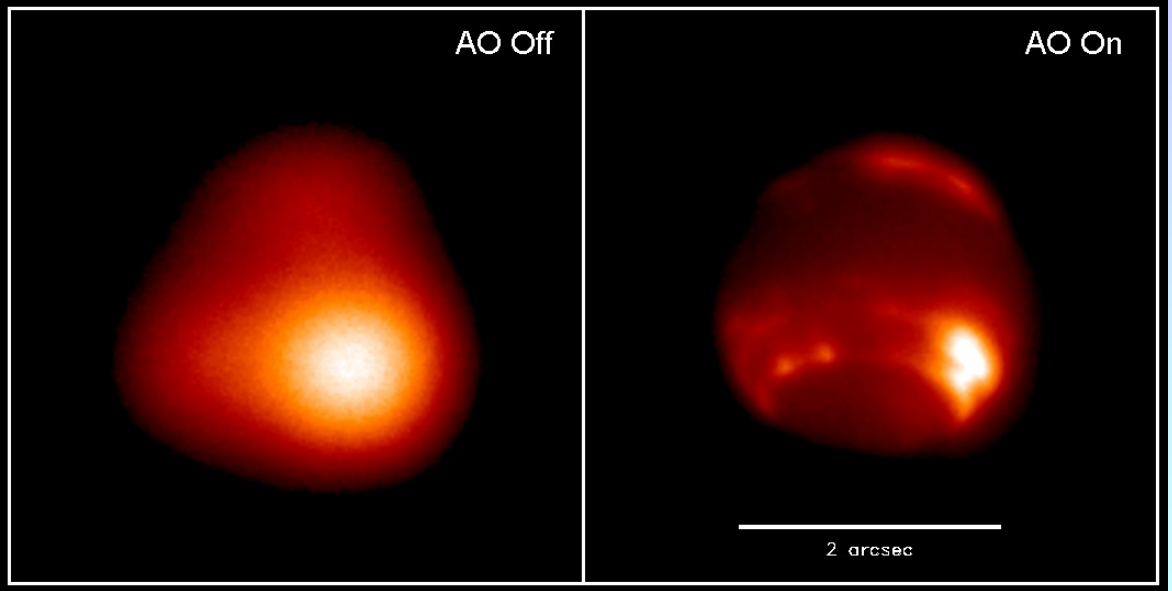
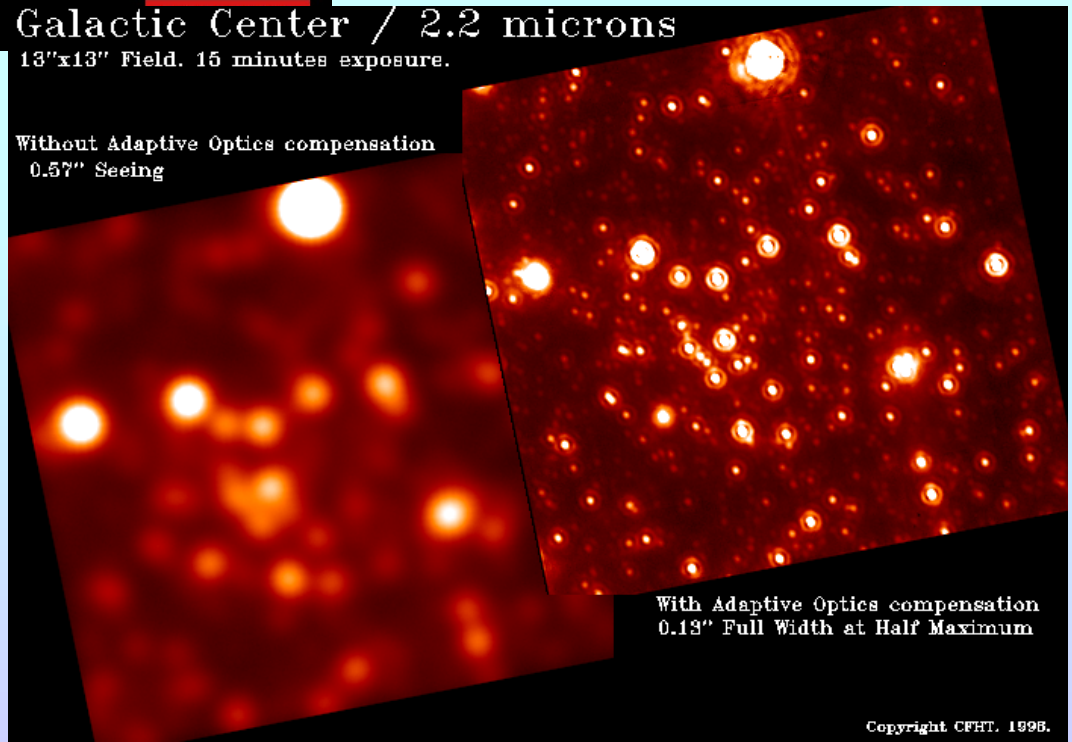
Note: to measure the wavefront, you need a point source within the isoplanatic patch. If there's no bright star around, you can try making one with sodium lasers.

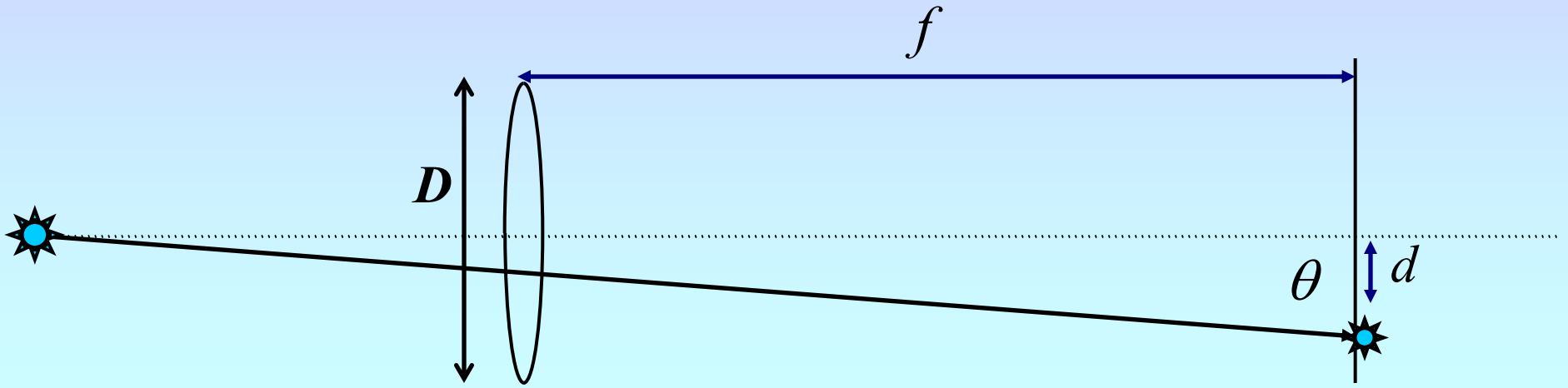


Results from Adaptive Optics (1.6 and 2.2 microns)

Adaptive Optics can achieve the diffraction limit in the near-IR



Telescope Size and Image Quality



Note: There is no sense in magnifying more than the telescope's seeing (or diffraction) limit: But note …

- The longer the focal length, the greater the magnification
- The larger the telescope, the faster the f-ratio needed to keep the focal length from delivering too large a magnification
- Fast optics are difficult to build! For large telescopes, excellent image quality is not a luxury – it's a necessity!

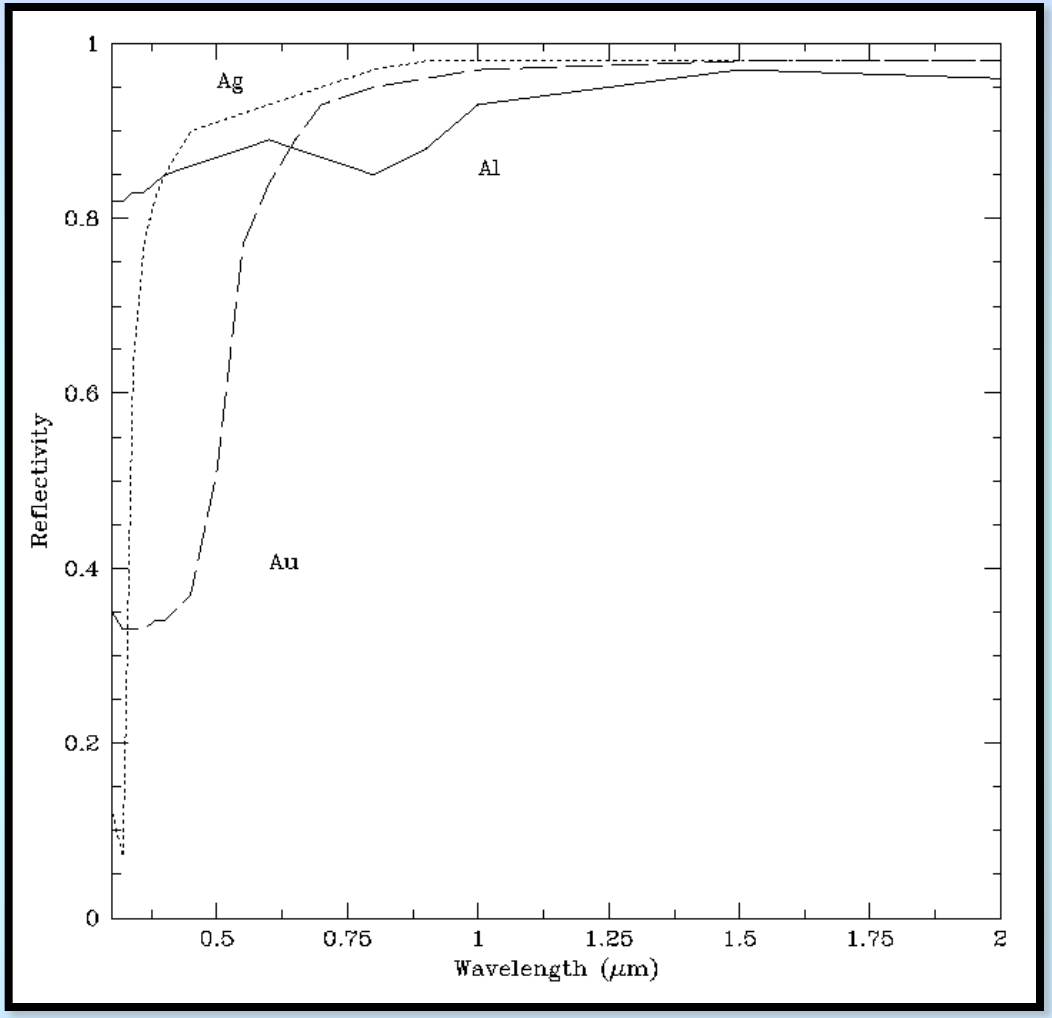
Mirror Coatings

There are 3 types of mirror coatings frequently used in near-UV/optical/IR astronomy:

Aluminum: Good reflectivity throughout optical and near-IR.

Silver: Better reflectivity longward of 4500 Å, but degrades quicker and dies in the blue.

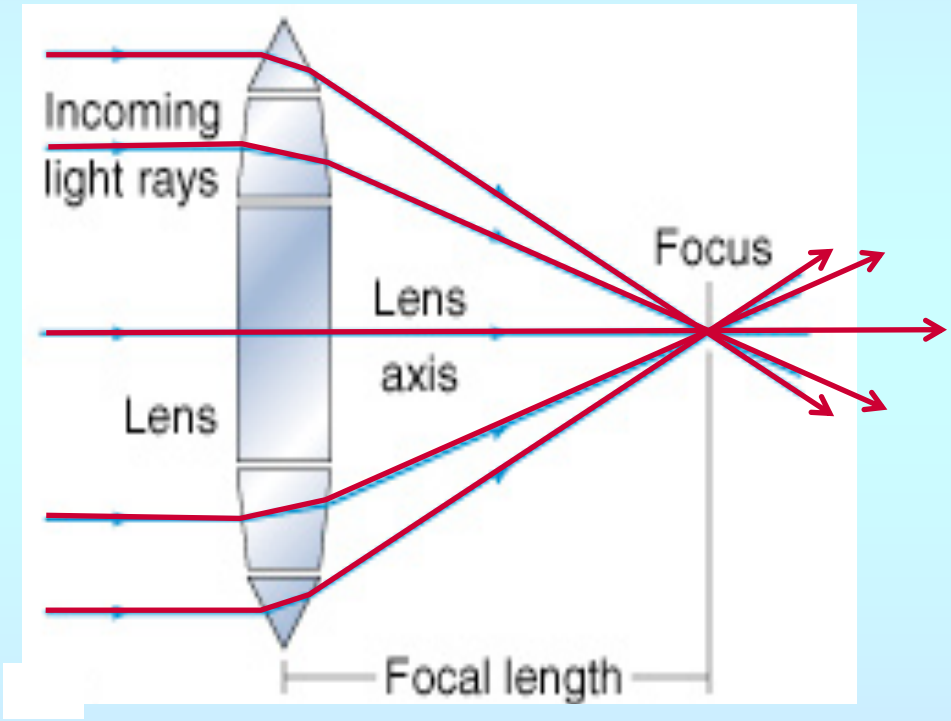
Gold: Even better reflectivity in the IR, but not good in the optical.

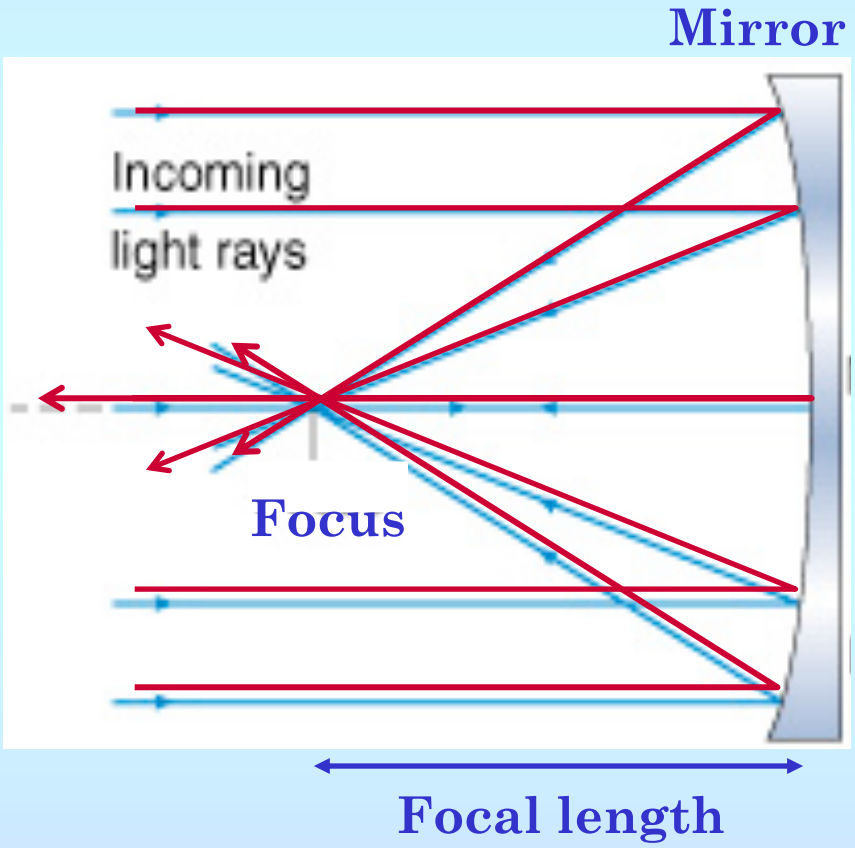


The difference between 90% and 95% reflectivity may not seem like much, but if there are 4 or 5 reflective elements, in multiplies up.

Classes of Telescopes

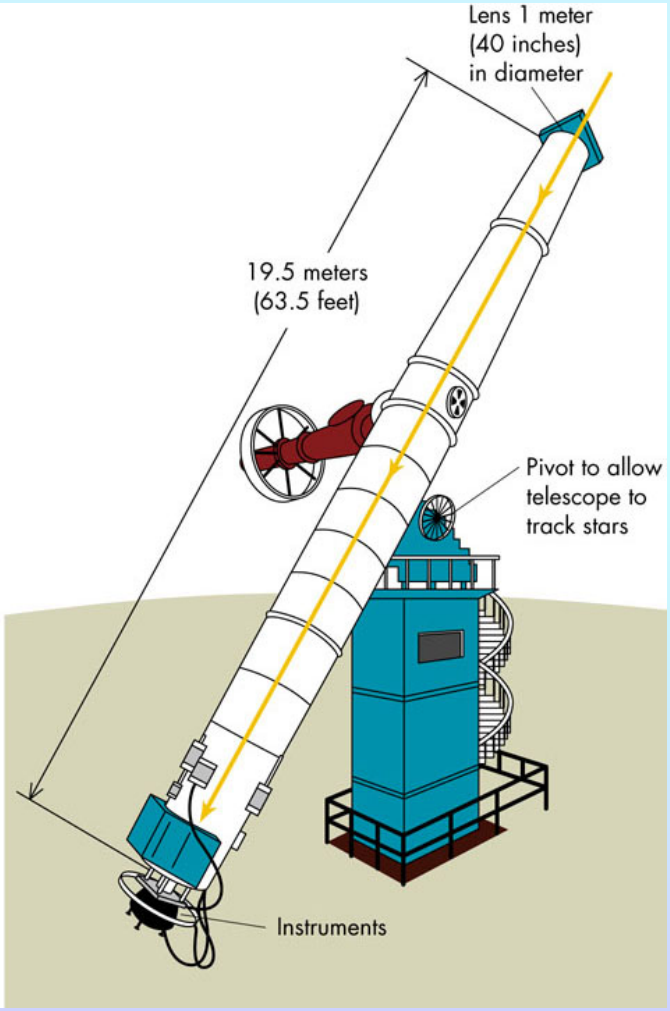
In the broadest terms, there are two classes of telescopes: **refracting** telescopes and **reflecting** telescopes.





Refracting Telescopes

Refractors use a lens to bring light to a focus. They are limited by a) large f-ratios, b) lens support issues, and c) chromatic aberration. The largest refractor is the 40-inch at Yerkes (Wisconsin).



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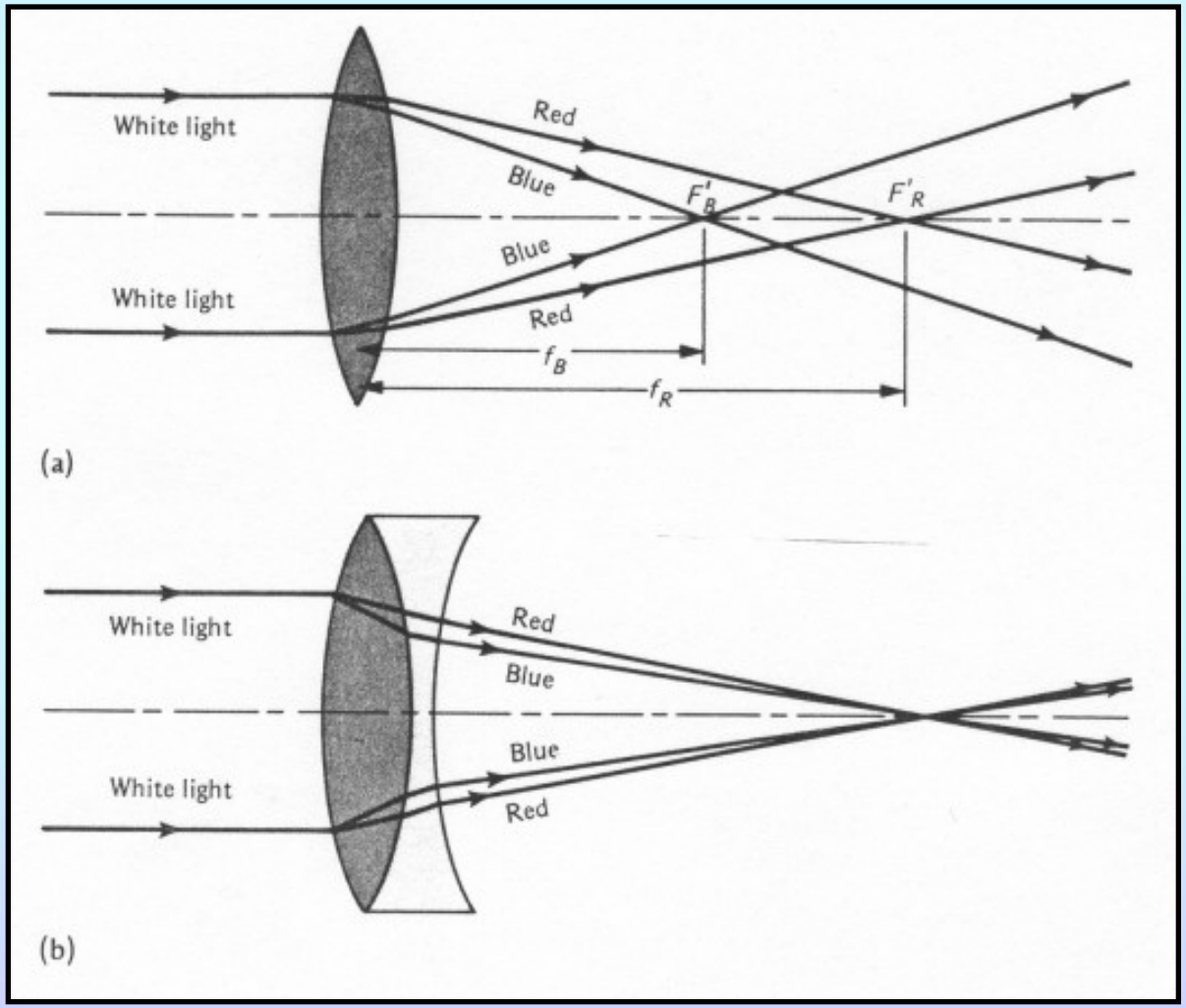

Chromatic aberration

Achromatic doublet (2 lenses of different glass)

Reflecting Ground-Based Telescopes

Reflecting telescopes use (a series of) mirrors to bring light to a focus. Virtually all professional telescopes are reflectors.

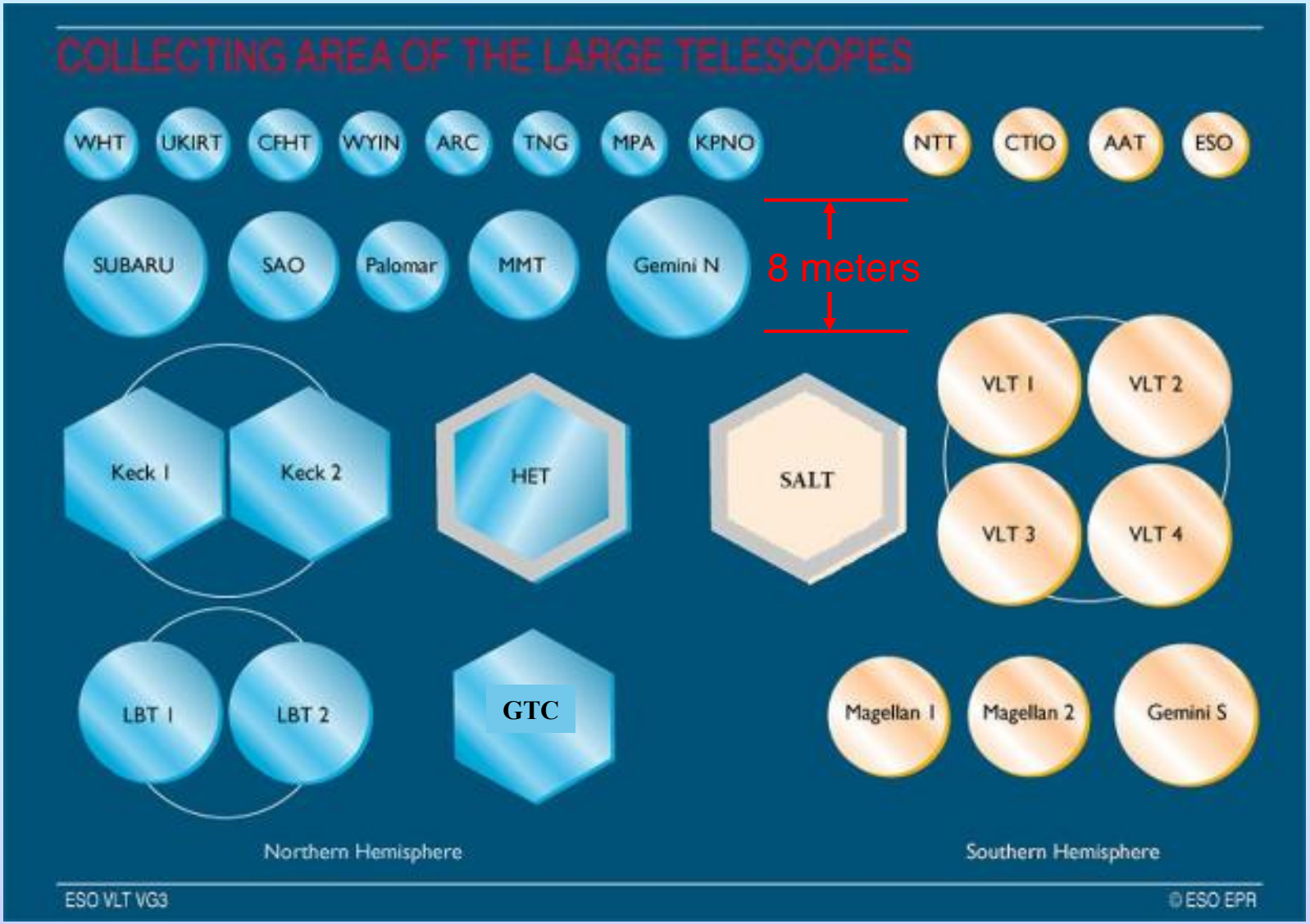

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Table C.1. The largest ground-based telescopes

Telescope	Location	Diameter (m)	Primary type	Primary f-ratio	Primary material	Mount	Date completed
LBT[1]	Arizona	11.8	honeycomb	1.14	E6	alt-az	(2004)
Keck I	Hawaii	10.5	segmented	1.75	Zerodur	alt-az	1993
Keck II	Hawaii	10.5	segmented	1.75	Zerodur	alt-az	1998
GTC	Canaries	10.4	segmented	1.65	Zerodur	alt-az	(2004)
Hobby-Eberly[2]	Texas	9.5	segmented	1.8	Zerodur	fixed	1999
SALT	South Africa	9.5	segmented	1.8	Zerodur	transit	(2004)
Subaru	Hawaii	8.4	meniscus	1.8	ULE	alt-az	1999
Gemini North	Hawaii	8.3	meniscus	1.8	ULE	alt-az	2000
Gemini South	Chile	8.3	meniscus	1.8	ULE	alt-az	2000
VLT UT1	Chile	8.2	meniscus	1.75	Zerodur	alt-az	1998
VLT UT2	Chile	8.2	meniscus	1.75	Zerodur	alt-az	1999
VLT UT3	Chile	8.2	meniscus	1.75	Zerodur	alt-az	2000
VLT UT4	Chile	8.2	meniscus	1.75	Zerodur	alt-az	2001
TIM	Mexico	7.0	segmented	1.5	Zerodur	alt-az	(2004)
MMT conversion[3]	Arizona	6.5	honeycomb	1.25	E6	alt-az	1999
Magellan I	Chile	6.5	honeycomb	1.25	E6	alt-az	1999
Magellan II	Chile	6.5	honeycomb	1.25	E6	alt-az	(2001)
BTA	Caucasia	6.0	solid	4	Sitall	alt-az	1976
LZT	Canada	6.0	liquid	1.6	mercury	transit	(2001)

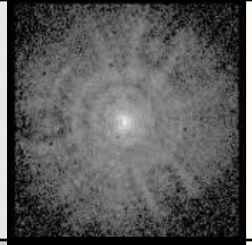
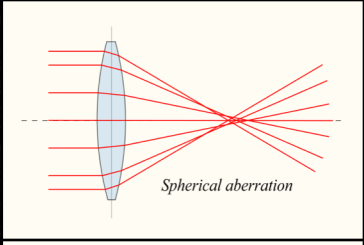
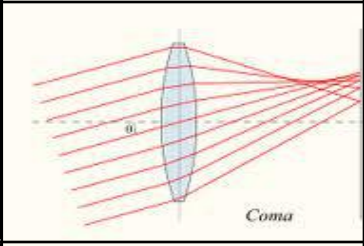
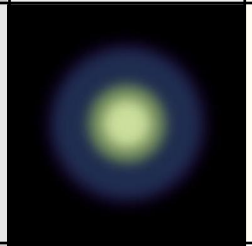
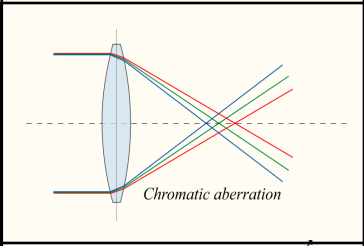
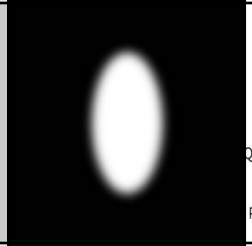
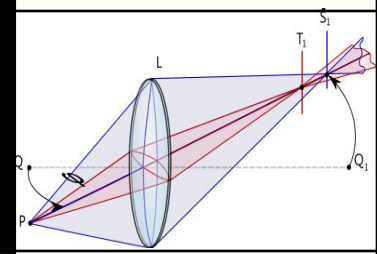
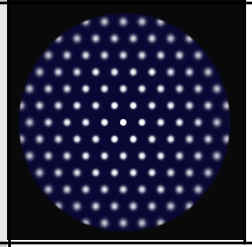
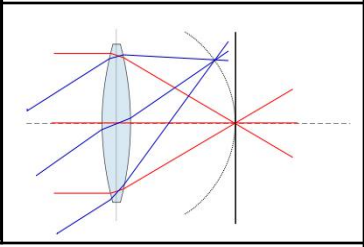
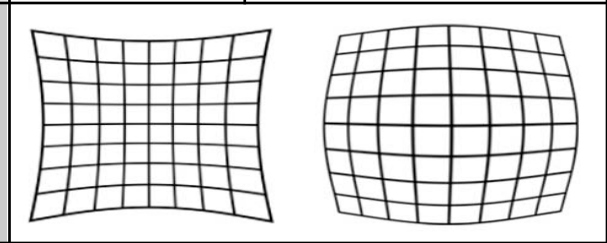
1. Two 8.4 m primary mirrors.
2. Fixed altitude mount; equivalent diameter.
3. Originally with six 1.8 m mirrors; 6 m mirror installed in 1999.

Aberrations

The goal of telescope design is to minimize image aberrations over as wide a field as possible.

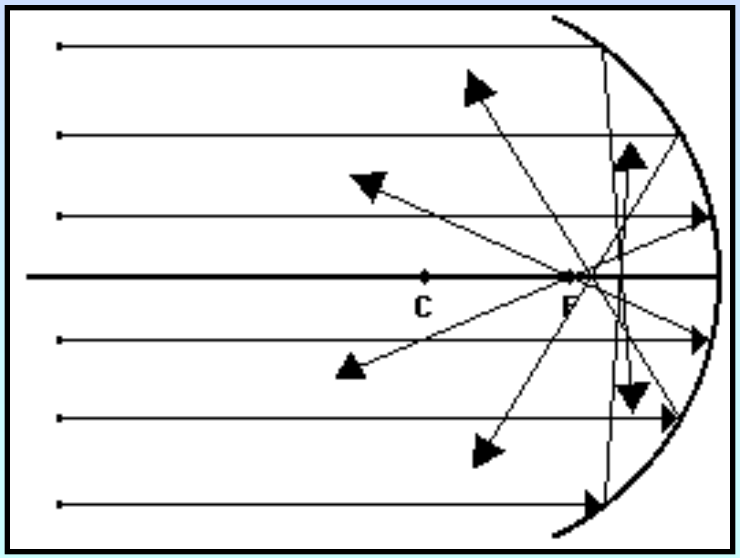
There is no perfect solution, so every design makes compromises between field-of-view, plate scale, image quality, feasibility, and expense.

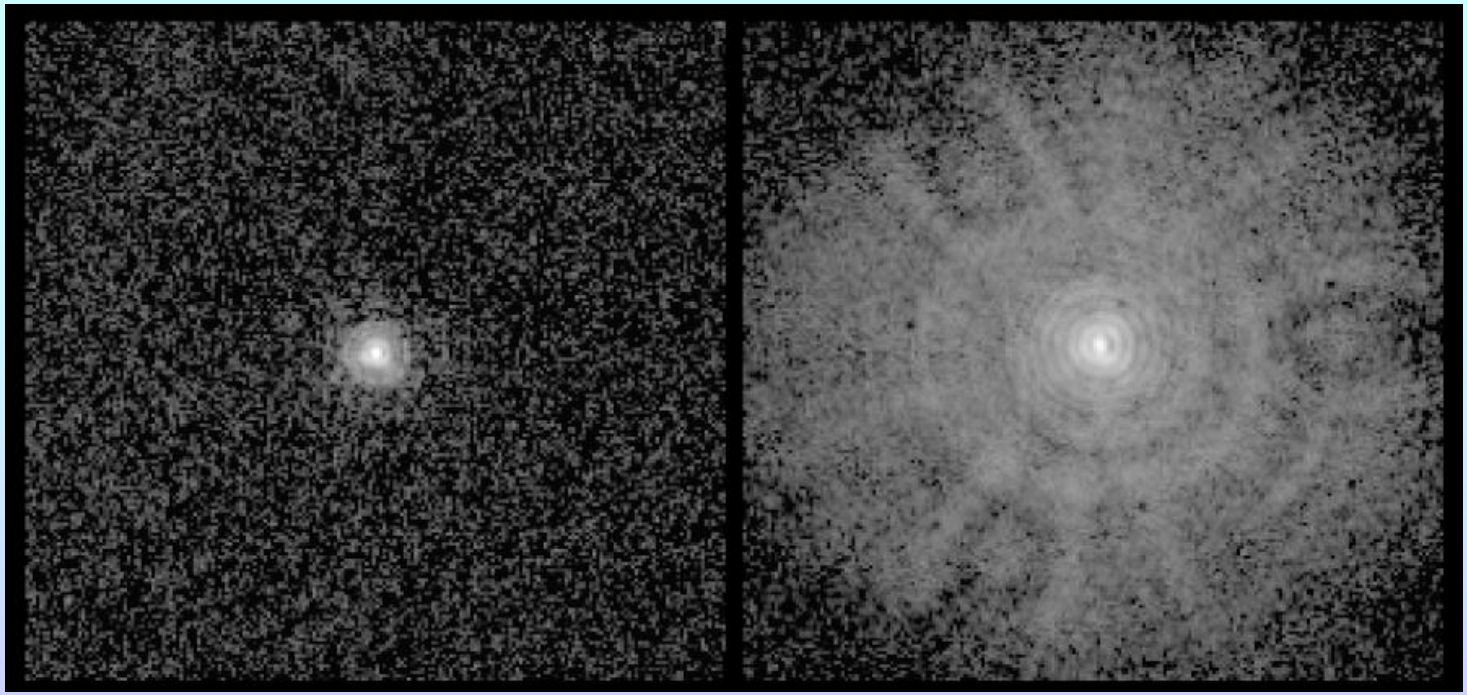
(For example, since the size of a telescope's dome is a significant expense, it saves money to make a telescope as fast as possible.)

Spherical		
Coma		
Chromatic		
Astigmatism		
Field Curvature		
Barrel and Pin-cushion Distortion		

Optical Design: Spherical Mirrors

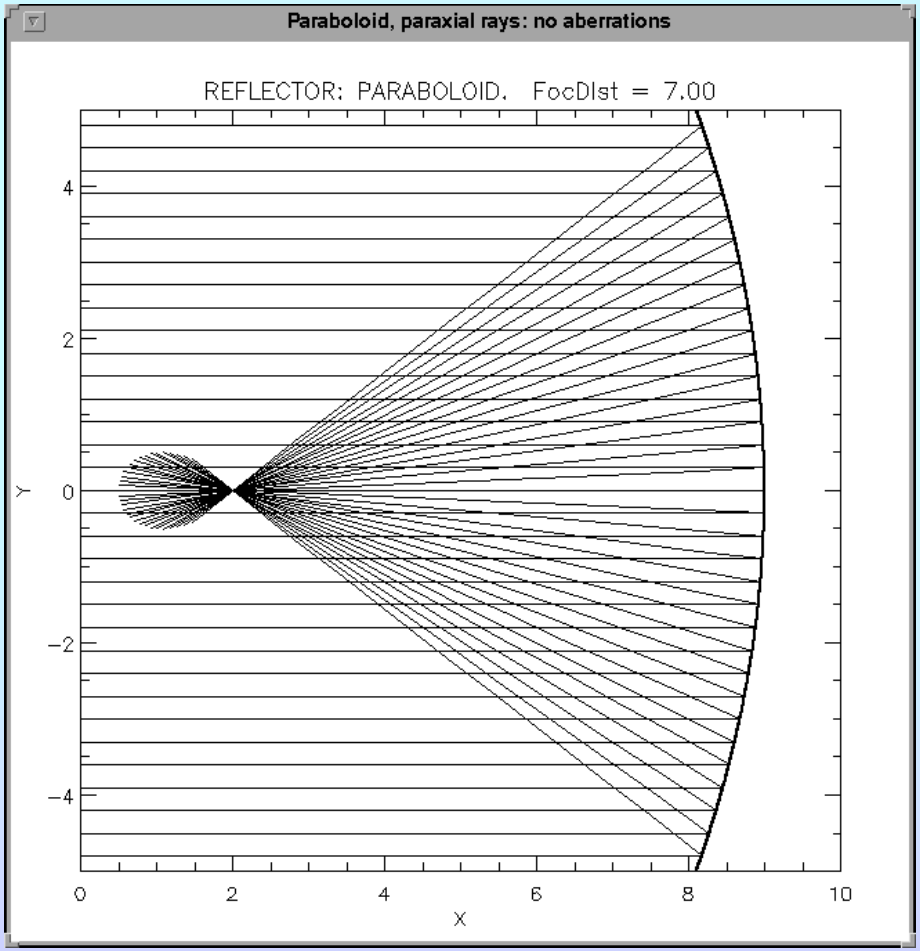
Spherical mirrors are easy to make and, through symmetry, terms such as coma and astigmatism are all zero. However, spherical mirrors (or lenses) do not bring light to a single focus. This is called spherical aberration.

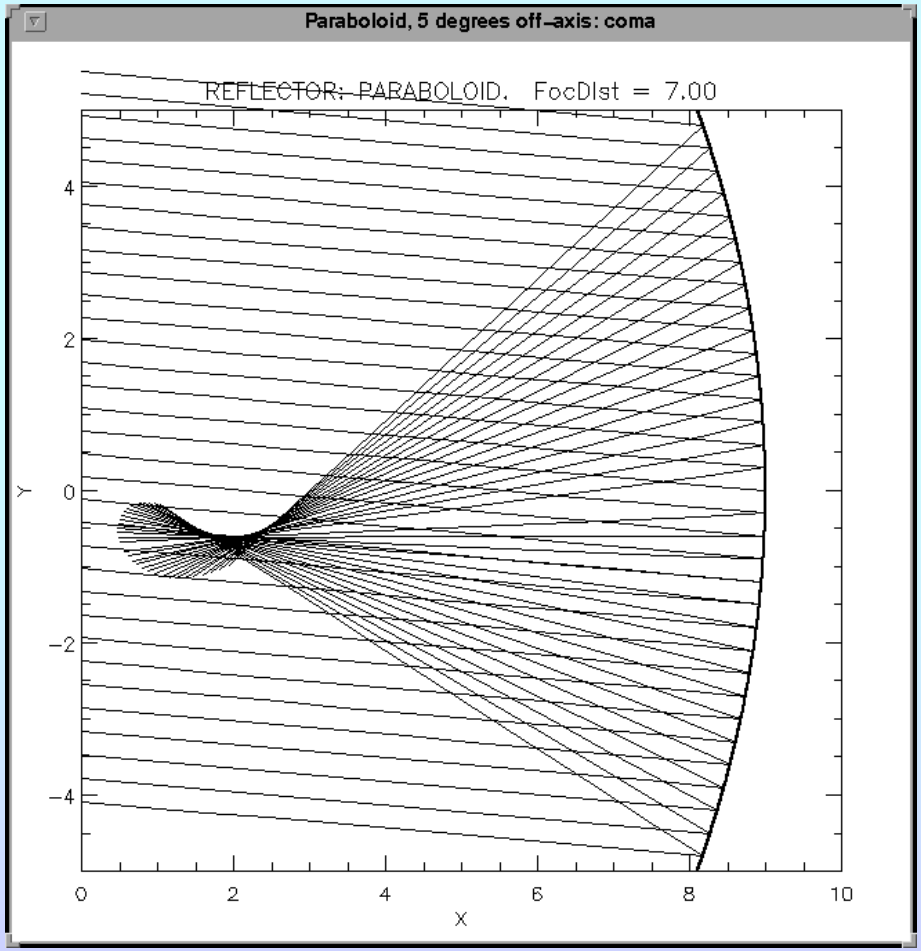




Optical Design: Parabolic Mirrors

Parabolic mirrors deliver perfect image quality for objects which are at the center of the field. But as the off-axis distance increases, so does the comatic aberration. Thus, most telescopes contain multiple optical elements to partially correct the distortions. But no design is perfect.





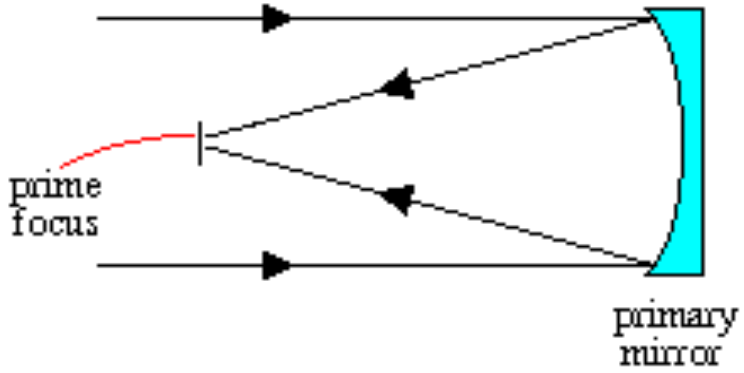
Telescope Configurations

Type	Primary Mirror	Secondary Mirror	Comments
Prime Focus	Parabola	none	Fewest number of reflections, but focus is inside the telescope. Refractive corrector needed to create a wider field of view.
Newtonian	Parabola	Flat	Focus at side/top of the telescope.
Cassegrain	Parabola	Hyperbola (convex)	(Optional) secondary placed in front of the primary focus, with system focus below the primary.
Gregorian	Parabola	Hyperbola (concave)	(Optional) secondary placed beyond the primary focus, with system focus below the primary.
Ritchey-Chretien	Hyperbola	Hyperbola (convex)	Secondary placed in front of the primary focus. No coma or spherical aberration, but no prime focus.
Coude	Any	Any	Tertiary flat directs light to fixed focus away from telescope (in controlled environment).
Nasmyth	Any	Any	(Moveable) tertiary flat directs light to focii at side of telescope.
Schmidt	Spherical	---	Refractive corrector removes spherical aberration. Can be designed for prime or Cassegrain focus.

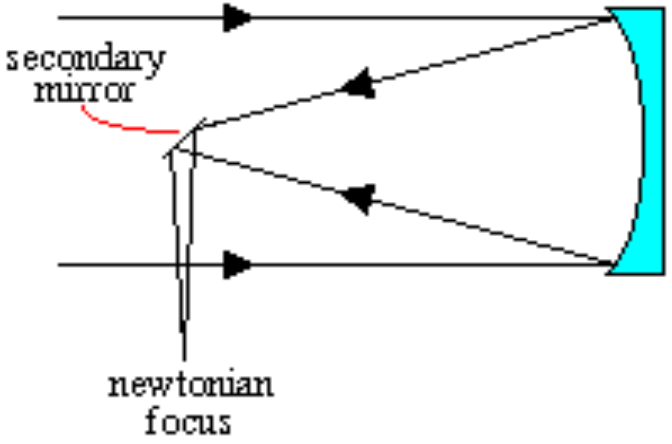
Basic Telescope Designs

Reflecting Telescopes

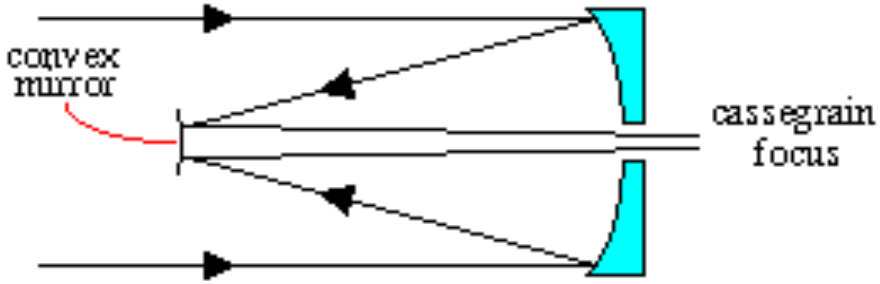
Prime



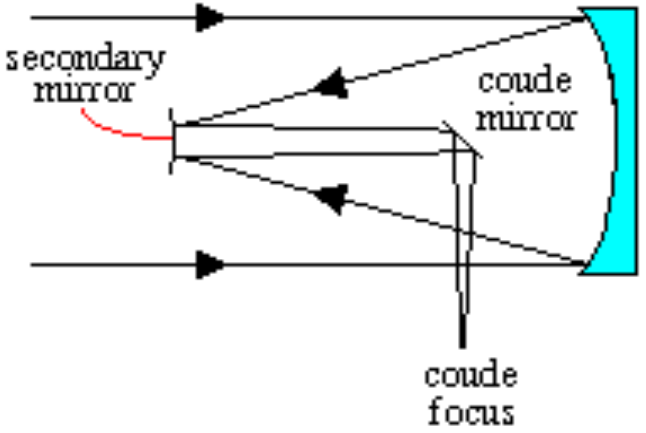
Newtonian

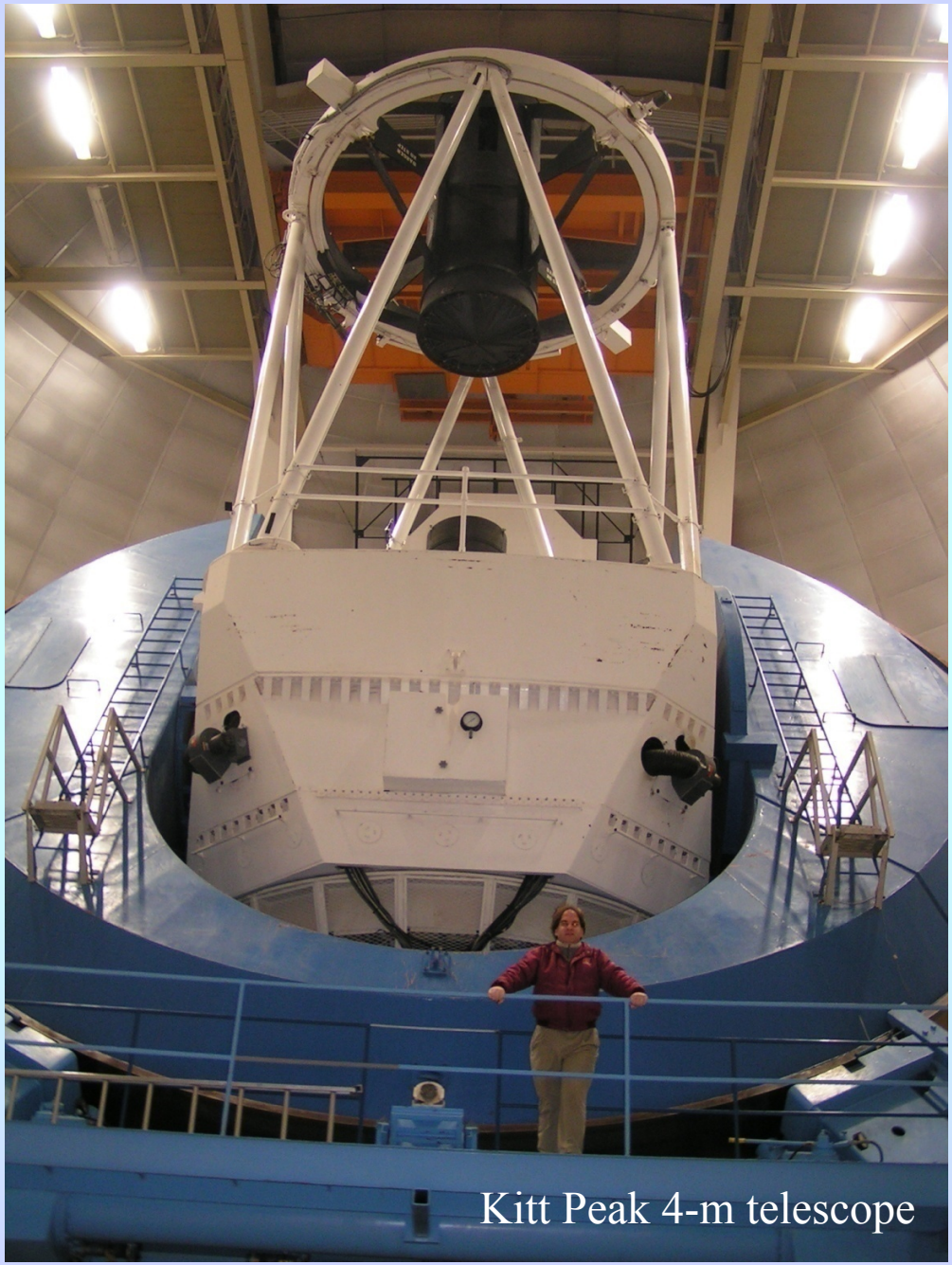


Cassegrain



Coude

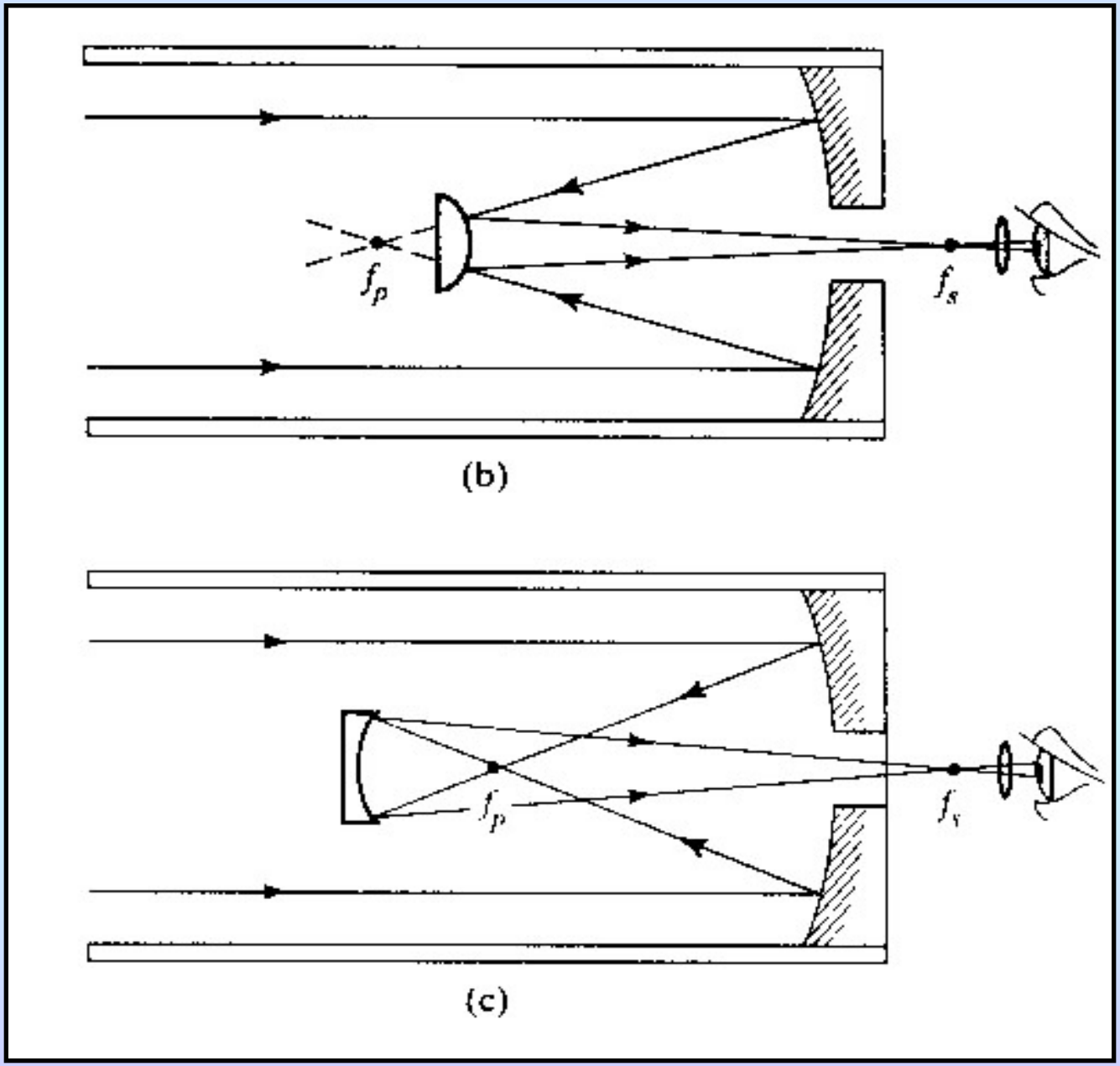




Kitt Peak 4-m telescope

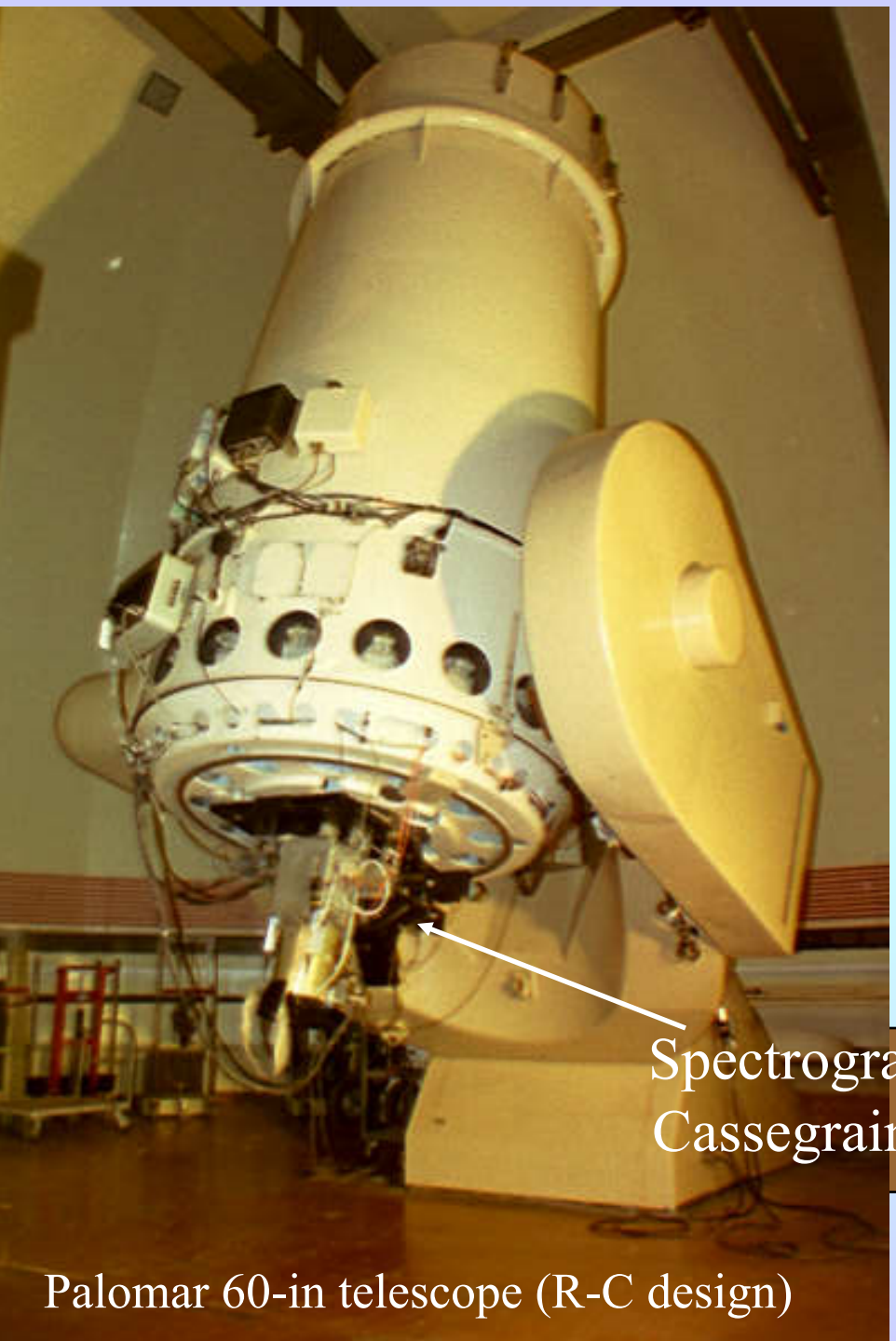
Palomar 5-m prime focus cage

Cassegrain versus Gregorian



Cassegrain

Gregorian



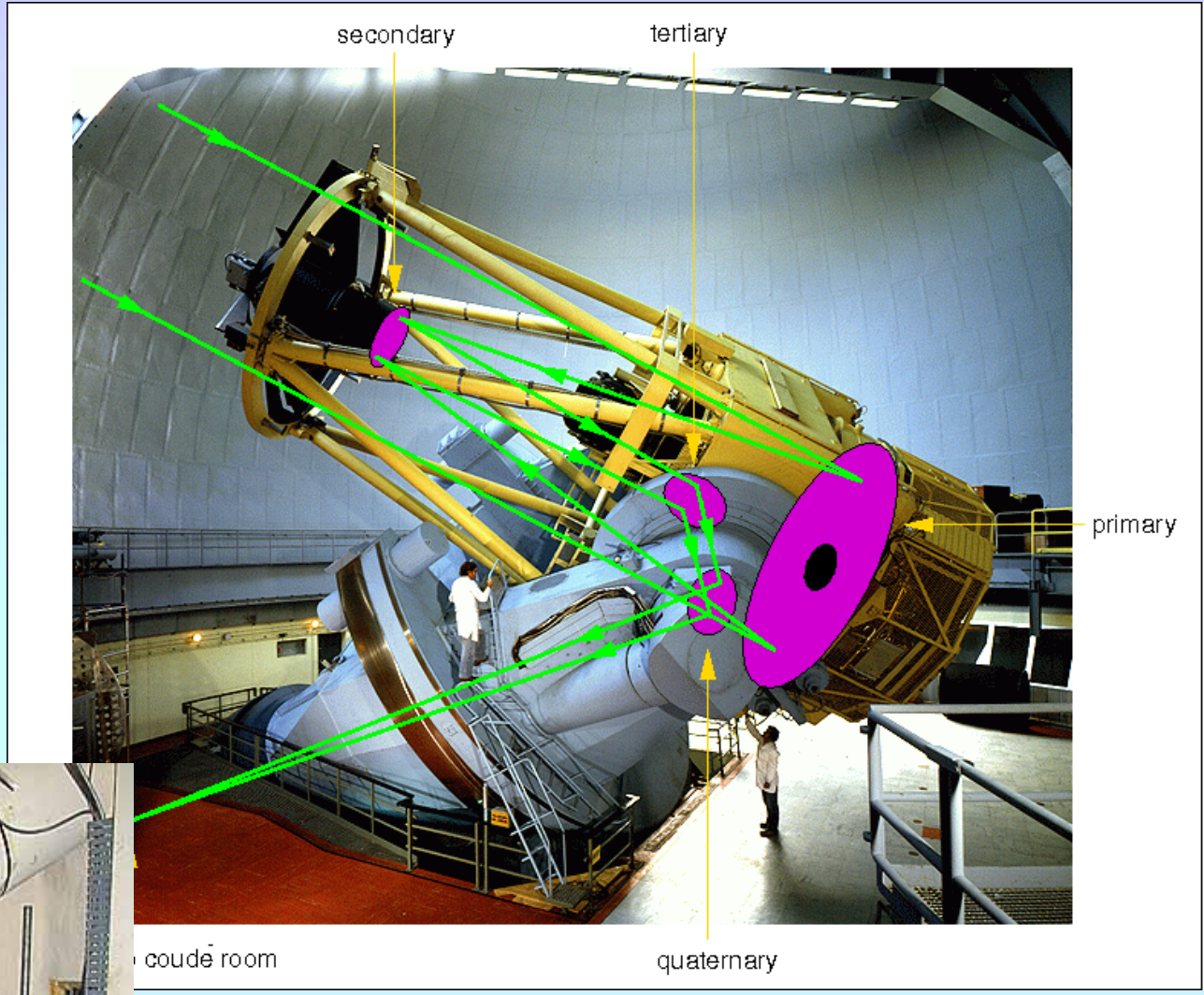
Palomar 60-in telescope (R-C design)

secondary mirror

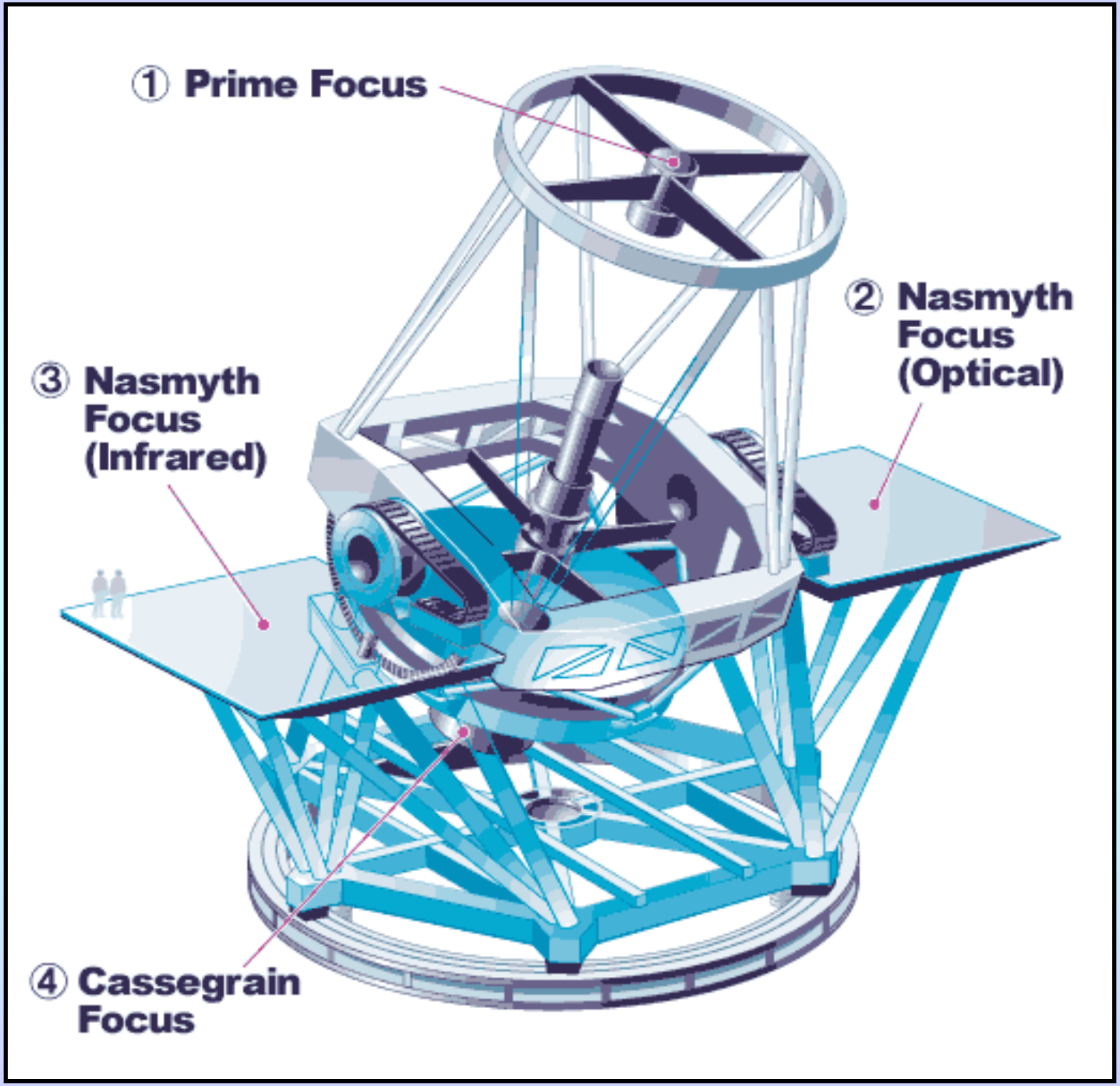
Spectrographs at
Cassegrain focus

DAO 1.8-m telescope

Coude Focus

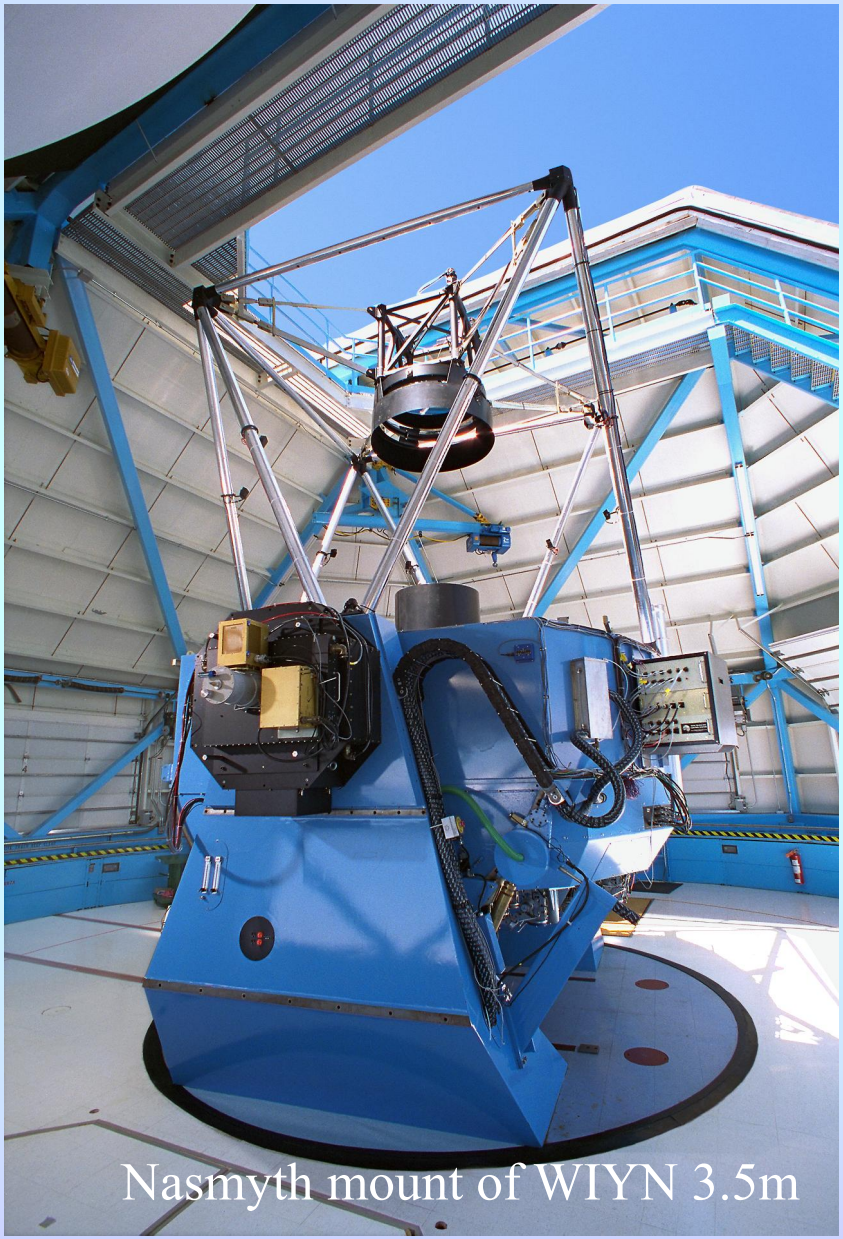


Coude instruments are kept in a separate room, generally for stability. They can be very large, and usually accept very slow beams.



Nasmyth mounts can hold heavy instruments, and all it takes is a quick flip of a small mirror to change from one instrument to another.

Examples of Nasmyth Mounts

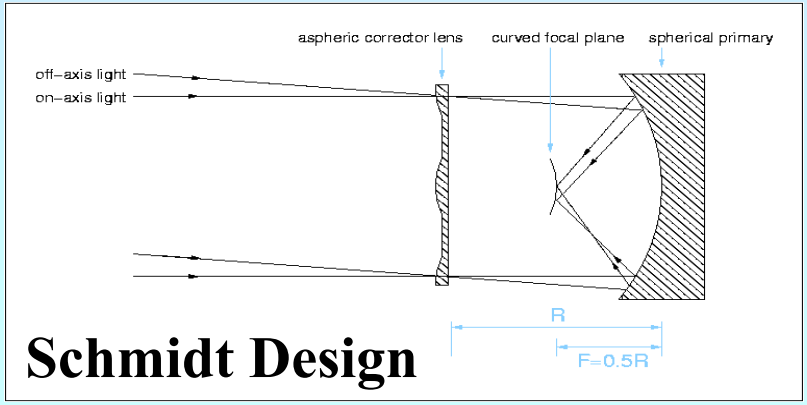


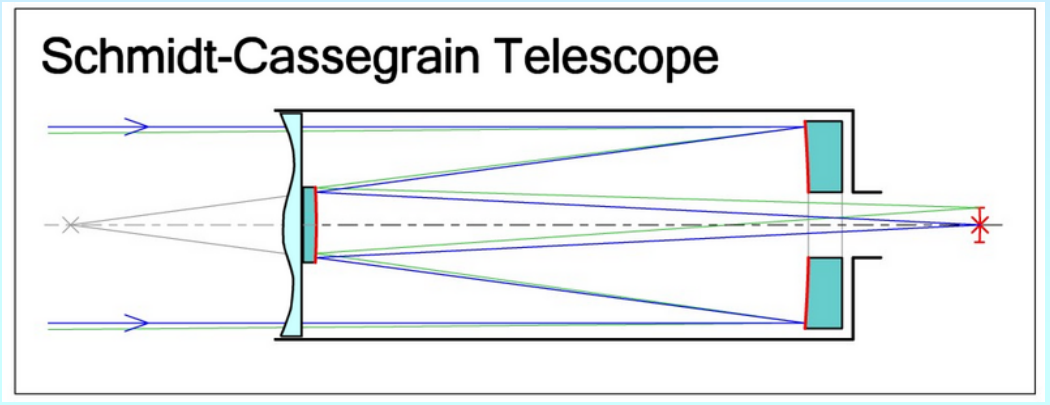
Nasmyth mount of WIYN 3.5m

VLT Instrument at Nasmyth

Schmidt Telescopes

Making spherical mirrors are easy. The limitations on the Schmidt design is the size of the aspheric corrector plate.

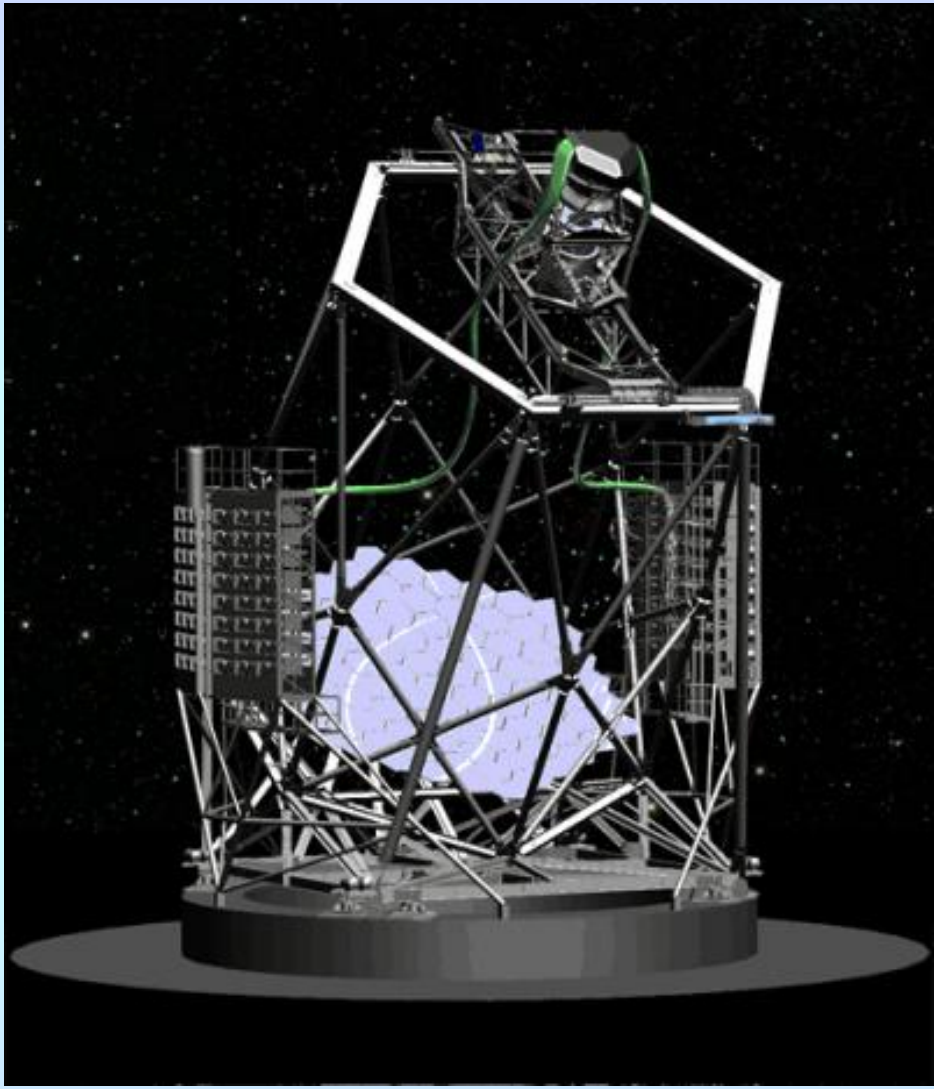




The Palomar 48-in is the largest full-field Schmidt telescope in the world, but the Schmidt-Cassegrain design is popular for small telescopes. Because the main mirror is spherical, the design can have a very large field-of-view.

Mauna Kea – Hawaii (at almost 14000 feet)

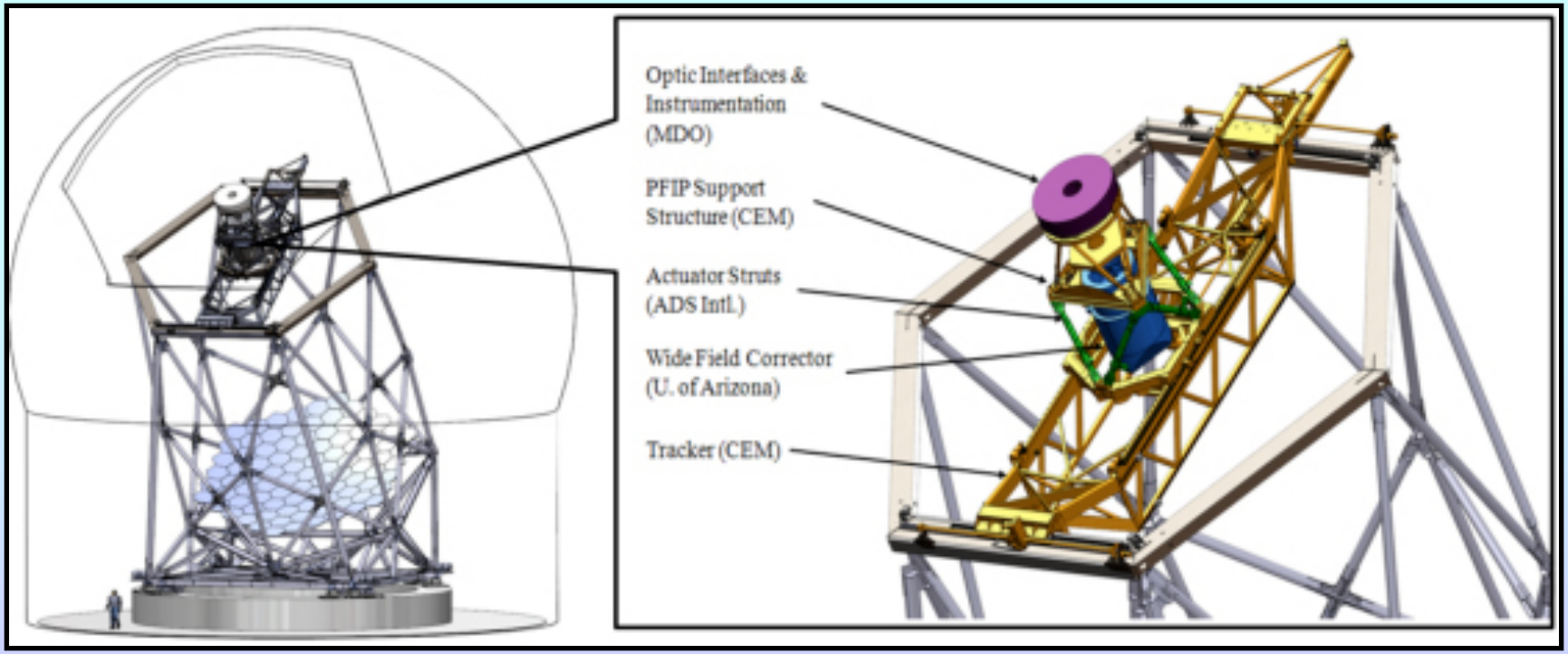
The Hobby Eberly Telescope



The HET has an 11.1-m spherical primary and a corrector which sees 10-m of the primary at a time.

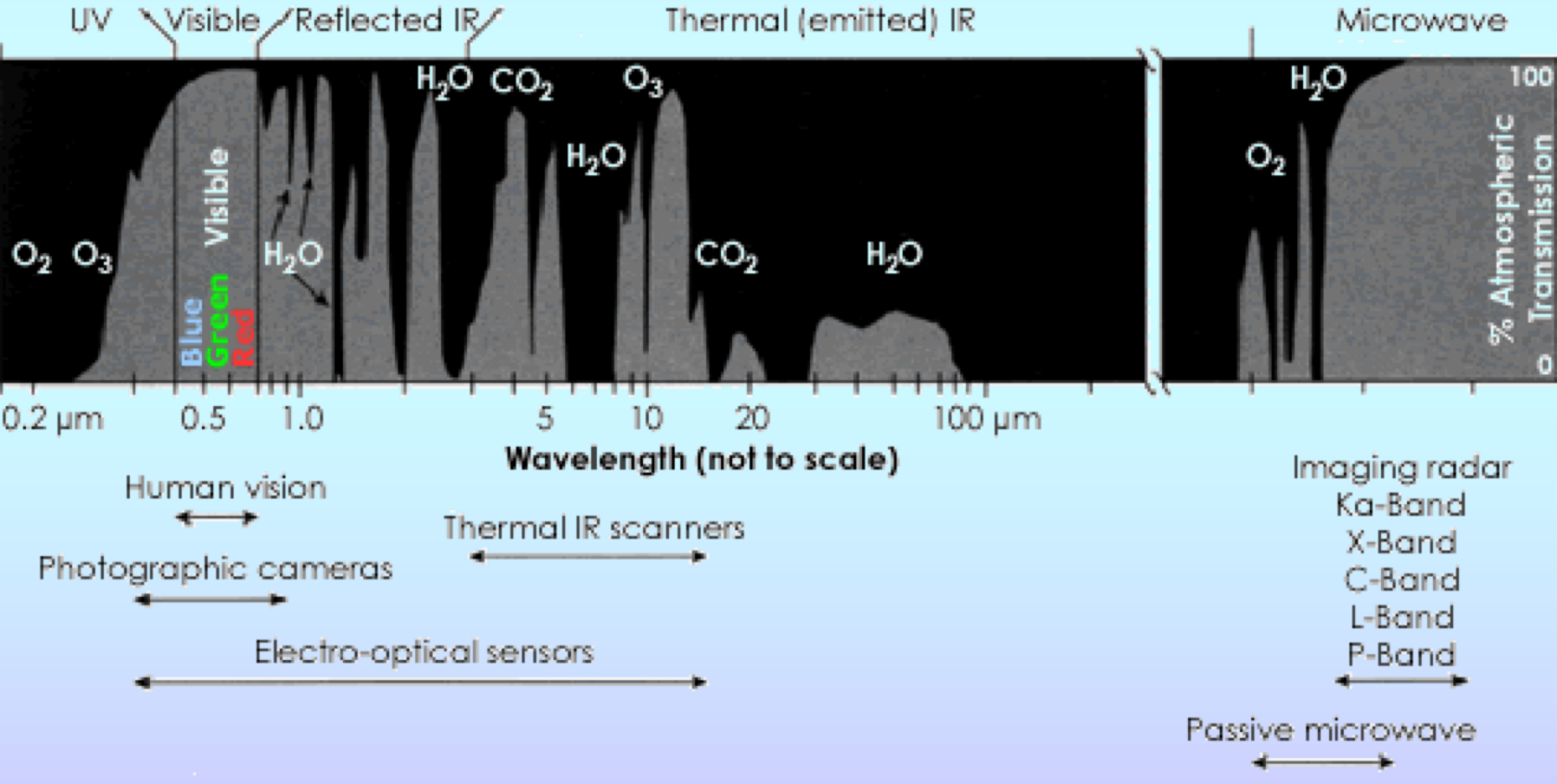
The Hobby Eberly Telescope

HET (and SALT) are fixed altitude telescopes tilted $z = 35^\circ$ (and 37°) from the zenith. The spherical primary delivers a 6° field-of-view and can be rotated in azimuth to enable access to declinations $\varphi \pm z$, (φ = latitude). A 4-element Gregorian spherical aberration corrector corrects a ~ 20′ region, and is attached to a tracker which follows the field across the primary. It takes between ~30 minutes and ~2.5 hours for objects to cross the mirror, depending on the declination.

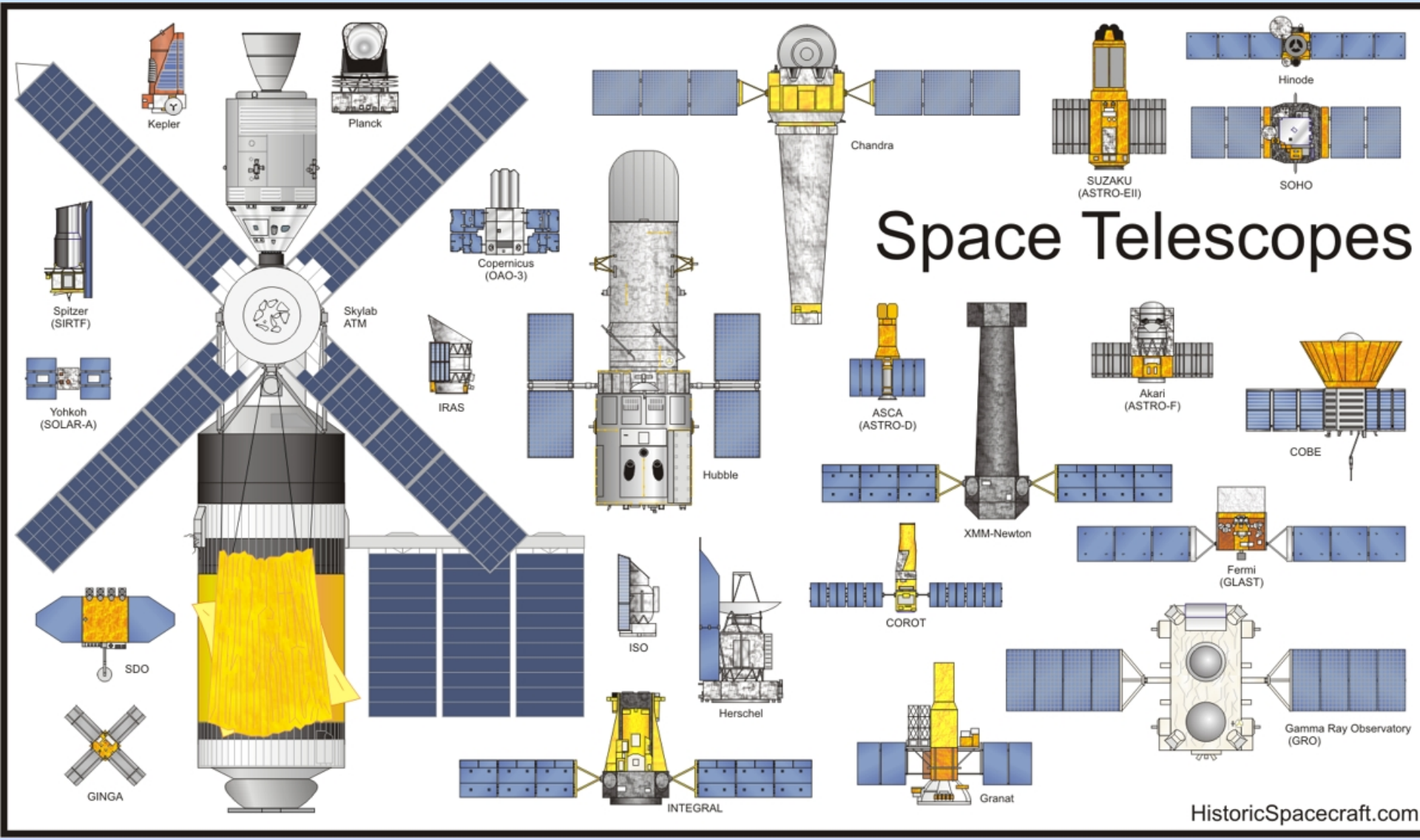


Atmospheric Windows

Our atmosphere is transparent to visible and radio light, and partially transparent in the infrared. For all other wavelengths, you need to go to space. (You also need space to avoid the effects of seeing.)

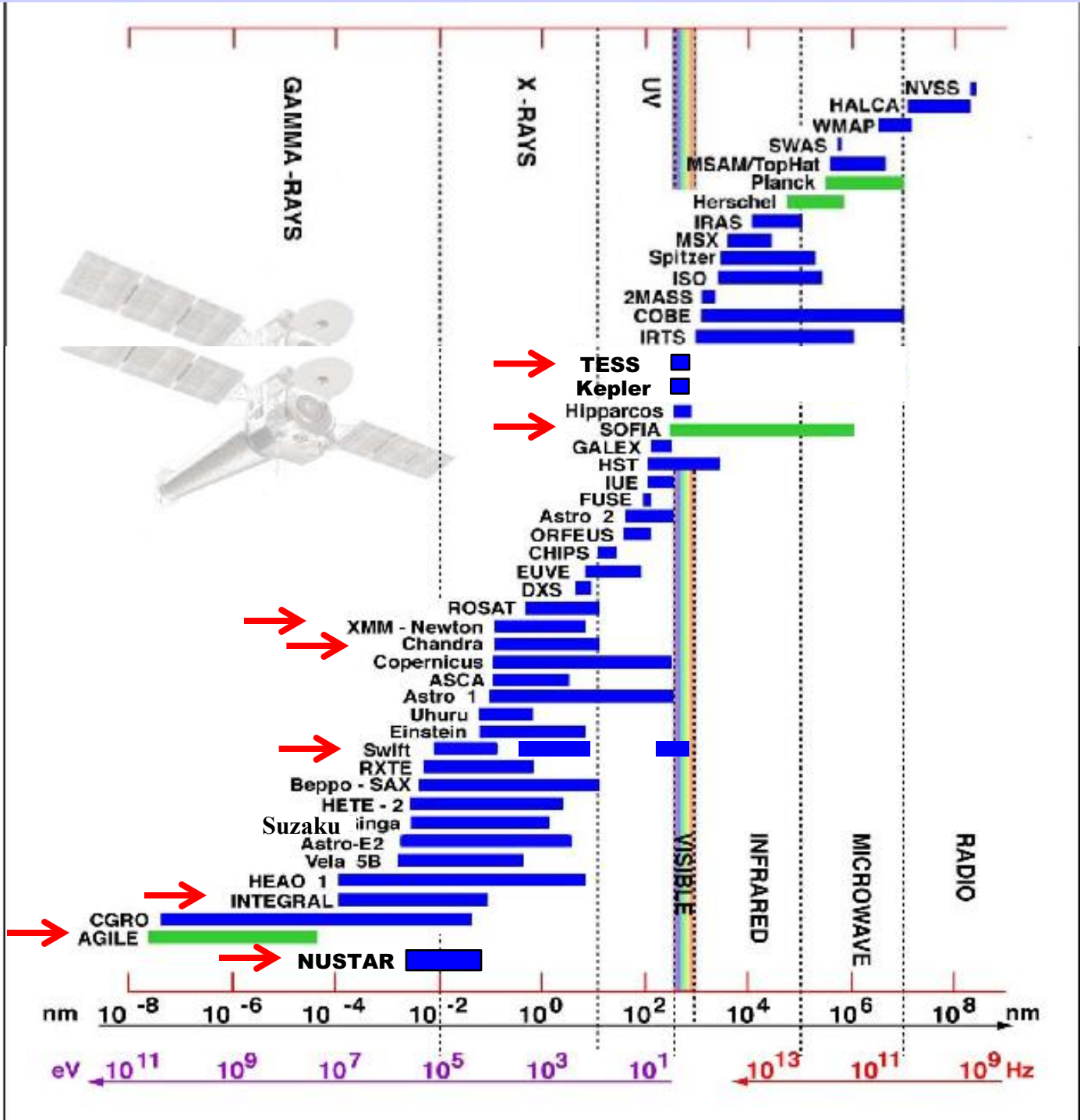


Telescopes in Space



Telescopes in Space by Wavelength

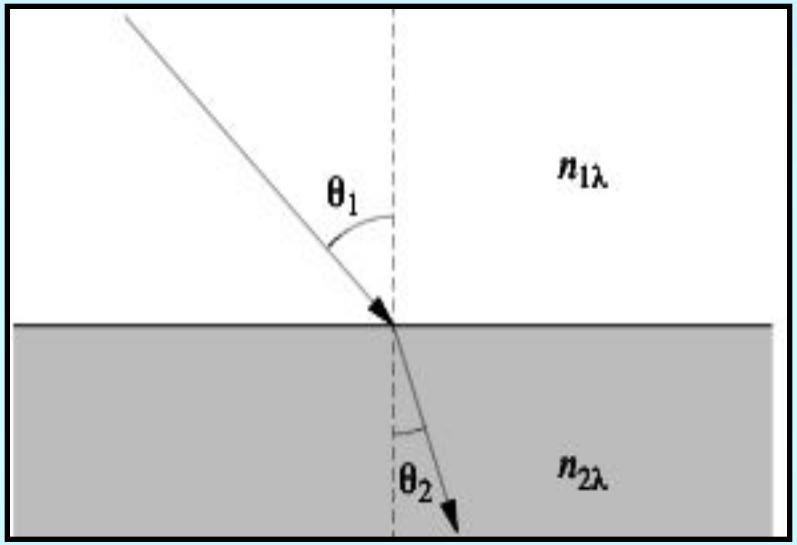
(red arrows note those telescopes that are still working)

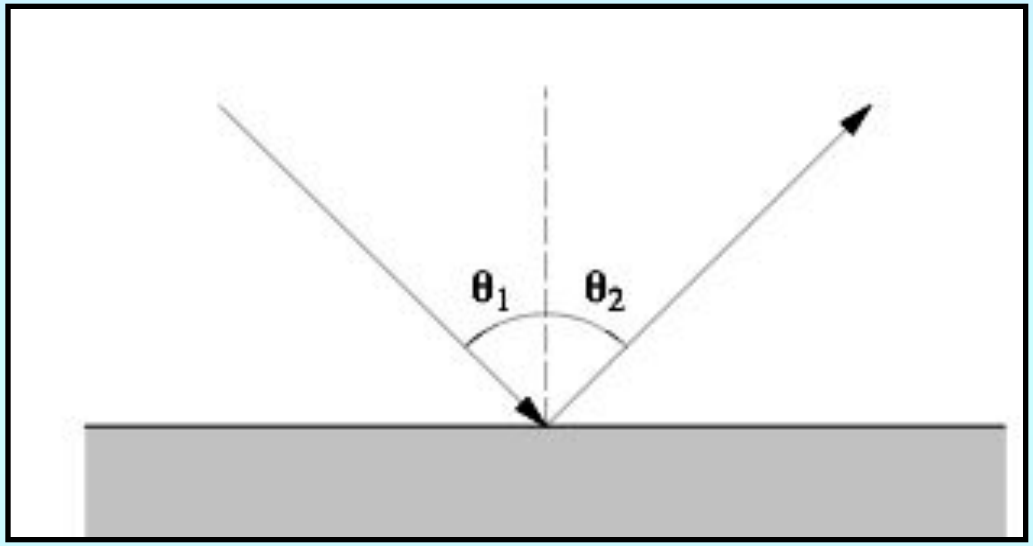


X-ray Telescopes

Materials do not generally reflect X-rays. However, according to Snell's Law:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

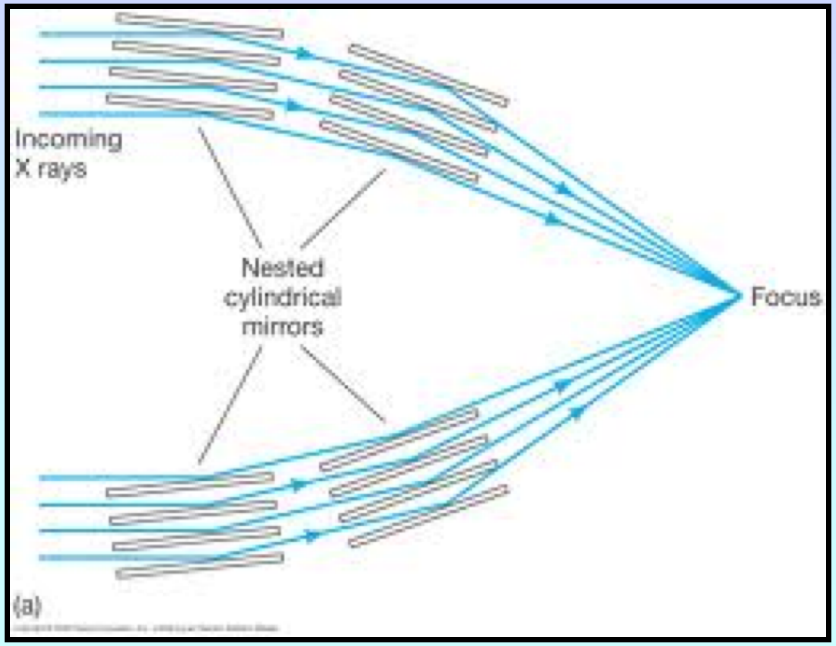




For a vacuum, $n_1 = 1$. For most mediums, $n_2 > 1$, but at X-ray wavelengths (and within plasmas), $n_2 < 1$. Thus, X-rays are efficiently reflected if they come in at a grazing incidence, so that

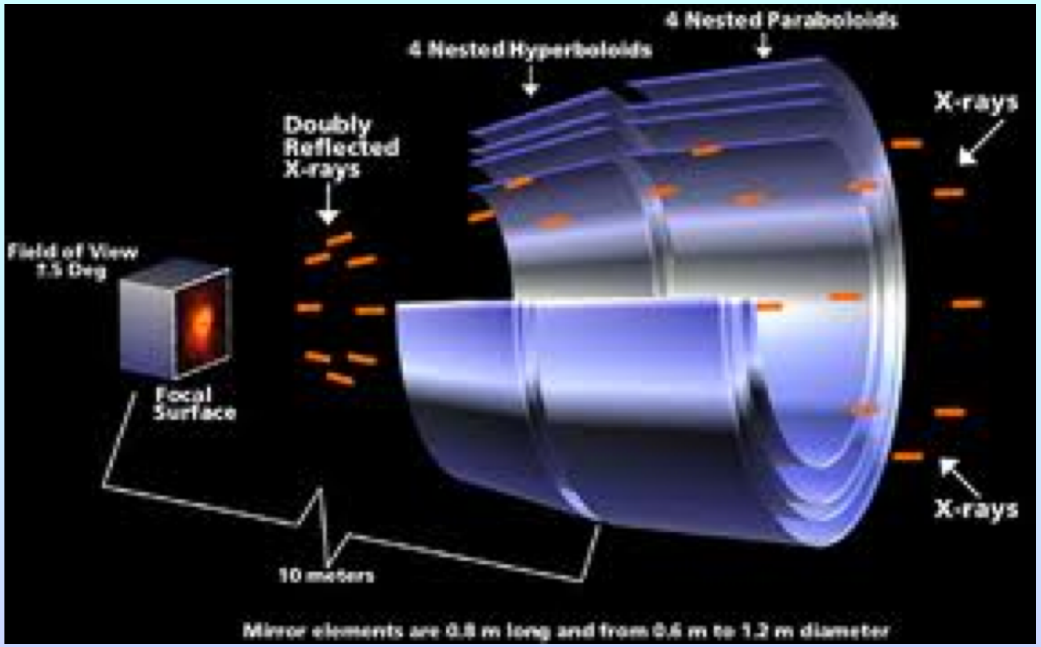
$$\theta_1 > \arcsin\left(\frac{n_2}{n_1}\right)$$

X-ray Telescopes



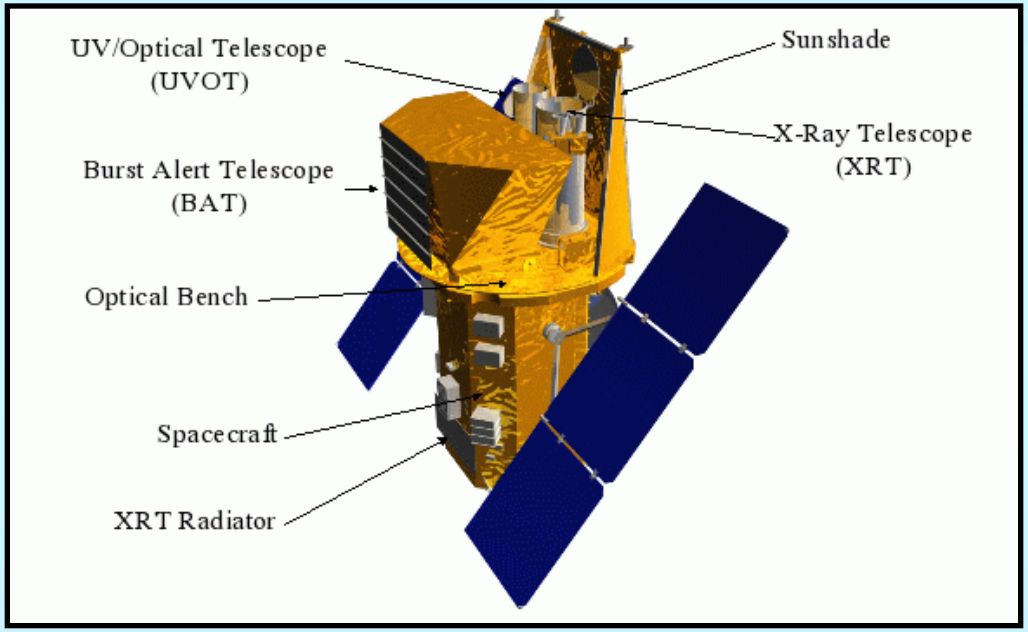
X-ray telescopes must have very long focal lengths to keep grazing angles low. In order to obtain significant collecting area, mirrors must be nested inside one another like Russian Matryoshka dolls.

Strong deviations from spherical reflection mean very large off-axis aberrations and a strongly curved focal surface.



The Swift Telescope

Swift is a rapid response spacecraft containing 3 separate telescopes: a UV/Optical Telescope (UVOT; 1700 Å – 5500 Å), an X-ray Telescope (XRT; 0.3 keV – 10 keV), and a Gamma-Ray Detector (BAT; 15 keV – 150 keV).

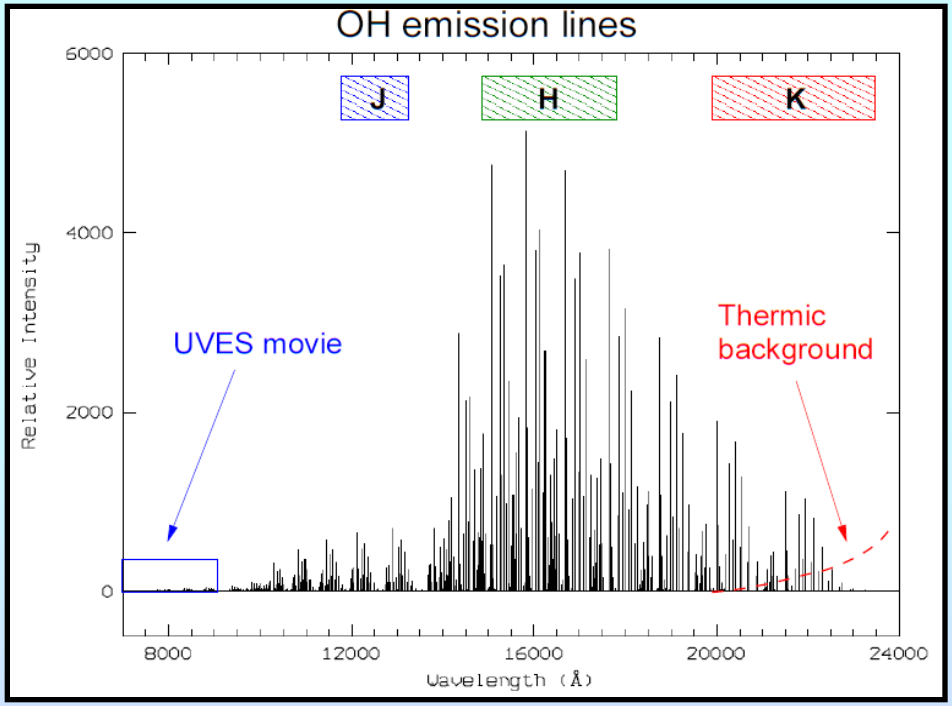


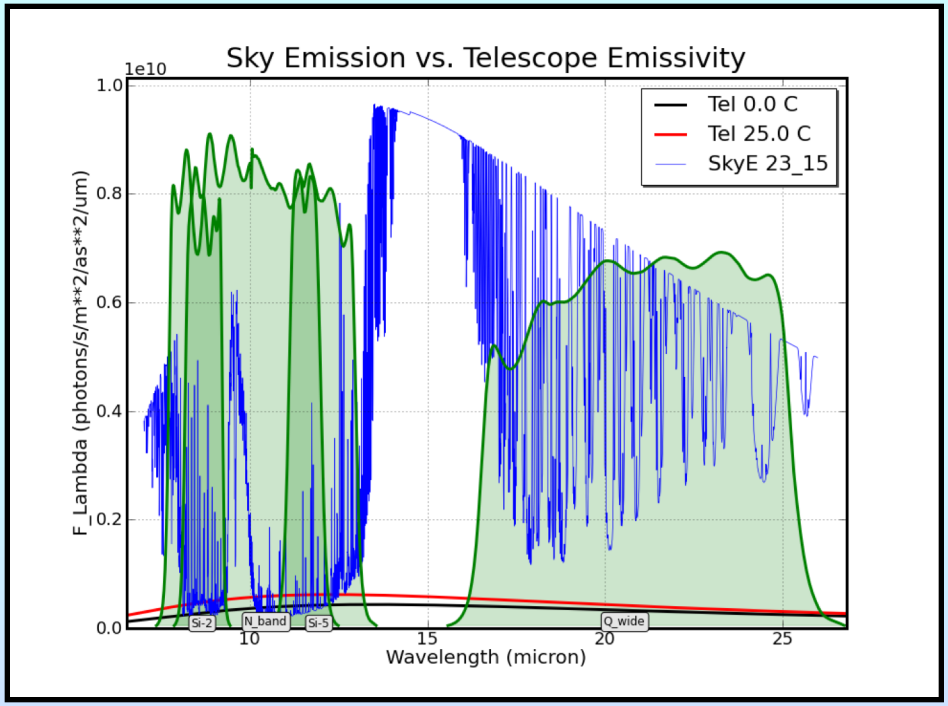
- The BAT observes 2 steradians of sky for γ-rays.
- The XRT and UVOT can localize a source to ~ 1″
- Swift can automatically slew to any object in the sky and send its data to the ground within seconds

Although originally purposed to investigate Gamma Ray Bursts, the telescope can be used for any project. Targets Of Opportunity (TOO) requests can be submitted via a simple web form, and several requests are received each day. (Almost all are accepted!)

Infrared and Millimeter Telescopes

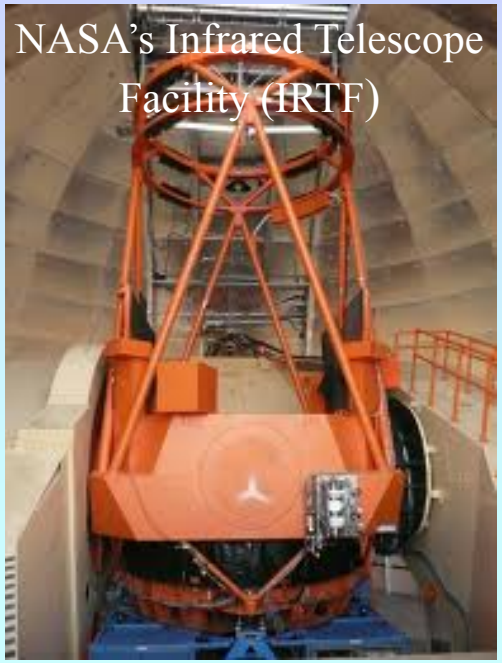
In the near IR, there are many strong, variable, atmospheric emission lines, mostly from OH and H_2O. This creates a high sky background (unless you observe at high resolution between the lines). At longer (IR and mm) wavelengths, sky emission, and the thermal background of the sky/telescope dominates.

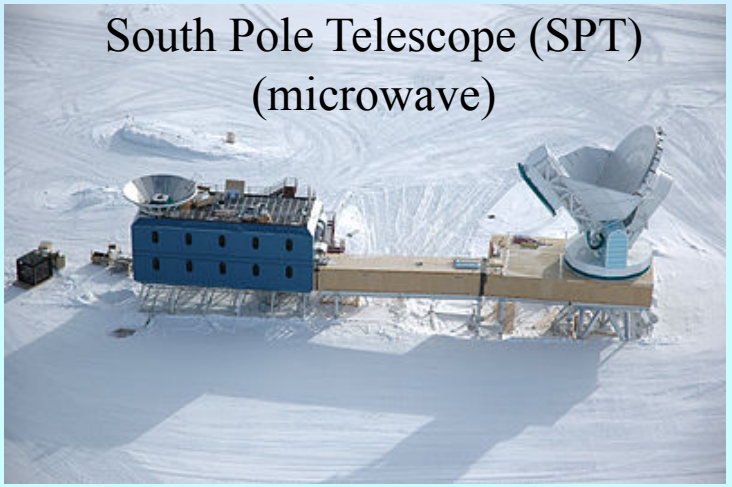


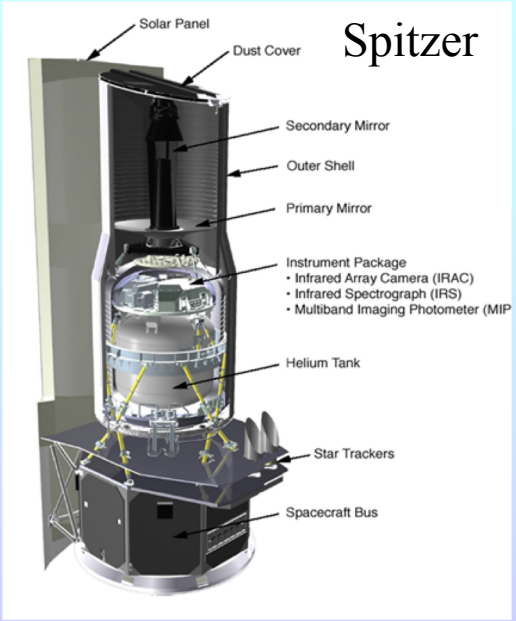
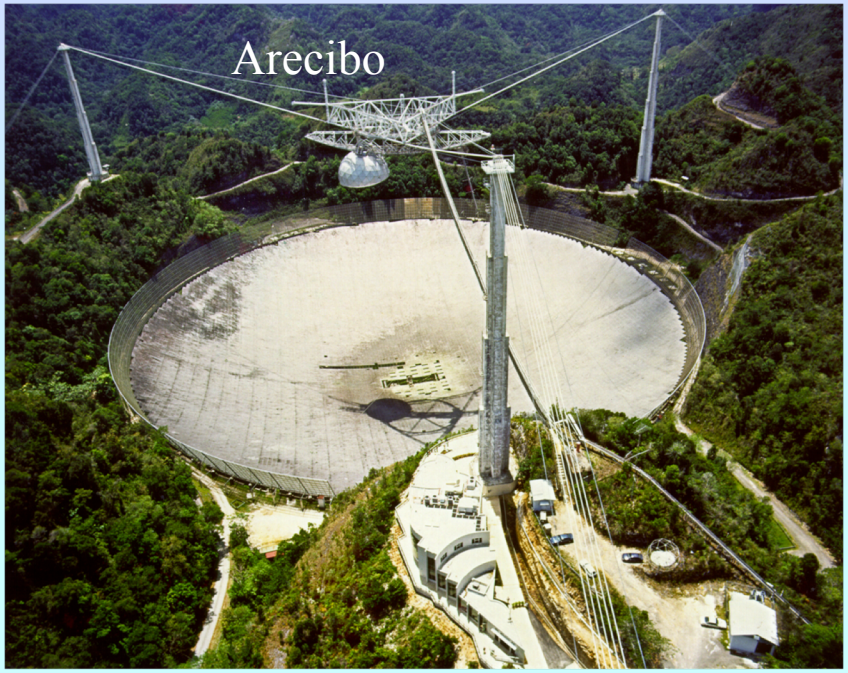
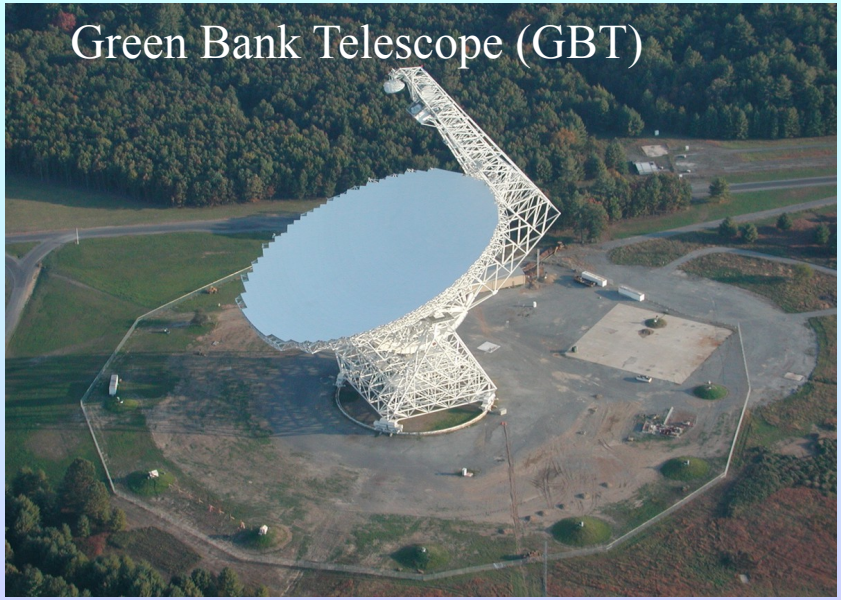


The solution is cold, dry sites, high altitude, and/or space.

Infrared and Sub-Millimeter Telescopes







Millimeter and Radio Telescopes